PSR Report 1419–3

AIRBLAST FROM NUCLEAR BURSTS—ANALYTIC APPROXIMATIONS

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July 1987

Technical Report
CONTRACT No. DNA 001-85-C-0089

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Prepared for
Director
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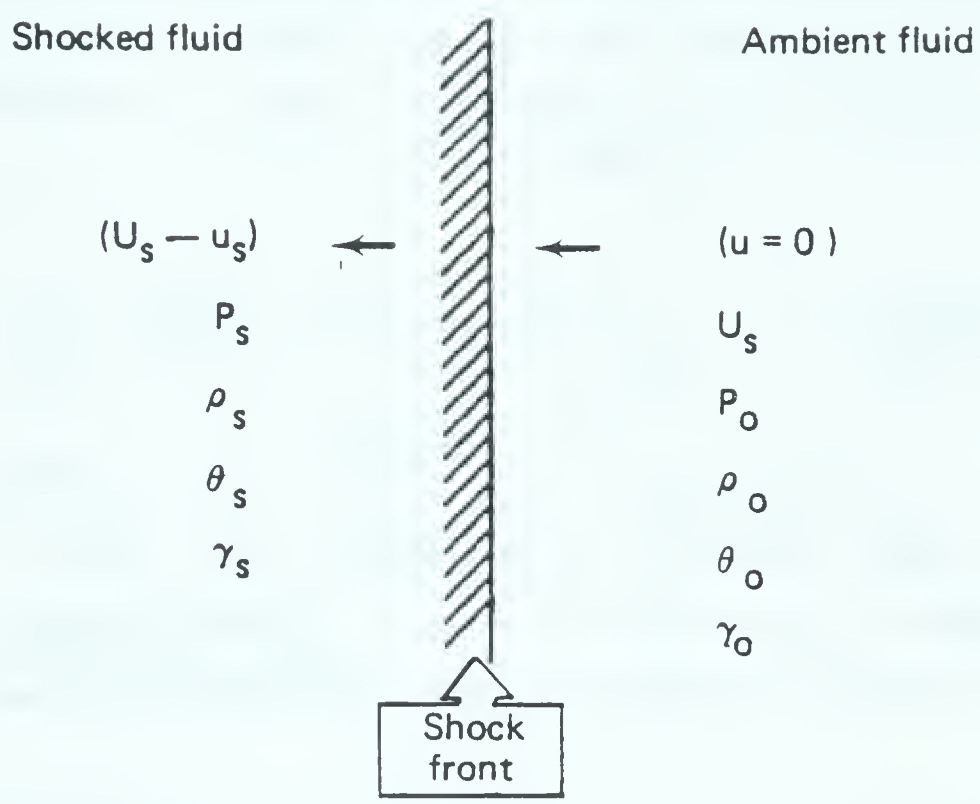


Figure 1. Shock-front parameters (in shock-front frame of reference).

$$\rho_o U_s = \rho_s (U_s - u_s) \qquad \text{(mass)}, \tag{1}$$

$$P_s - P_o = \rho_o u_s U_s \qquad \text{(momentum)}, \tag{2}$$

$$\frac{1}{2} U_s^2 + \frac{\gamma_o}{(\gamma_o - 1)} \frac{P_o}{\rho_o} = \frac{1}{2}(U_s - u_s)^2 + \frac{\gamma_s}{(\gamma_s - 1)} \frac{P_s}{\rho_s} \qquad \text{(energy)}. \tag{3}$$

Equation (3) may also be written as

$$E_s - E_o = \frac{P_s}{(\gamma_s - 1)\rho_s} - \frac{P_o}{(\gamma_o - 1)\rho_o} = \frac{(P_s + P_o)}{2} \left(\frac{1}{\rho_o} - \frac{1}{\rho_s} \right), \tag{4}$$

where E_s = shocked specific internal energy,

E_o = ambient specific internal energy.

Implicit in Eqs. (3) and (4) is the ideal gas relation for specific internal energy E:

$$E = P/[\rho(\gamma - 1)] \ ,$$

and (or)

$$P/\rho^{\gamma} = \text{constant} \ , \tag{5}$$

for adiabatic flows, in which γ is the specific heat ratio, $\gamma \equiv C_p/C_v$, where C_p is the specific heat at constant pressure, and C_v is the specific heat at constant volume, and where $P \equiv$ pressure and $\rho \equiv$ density.

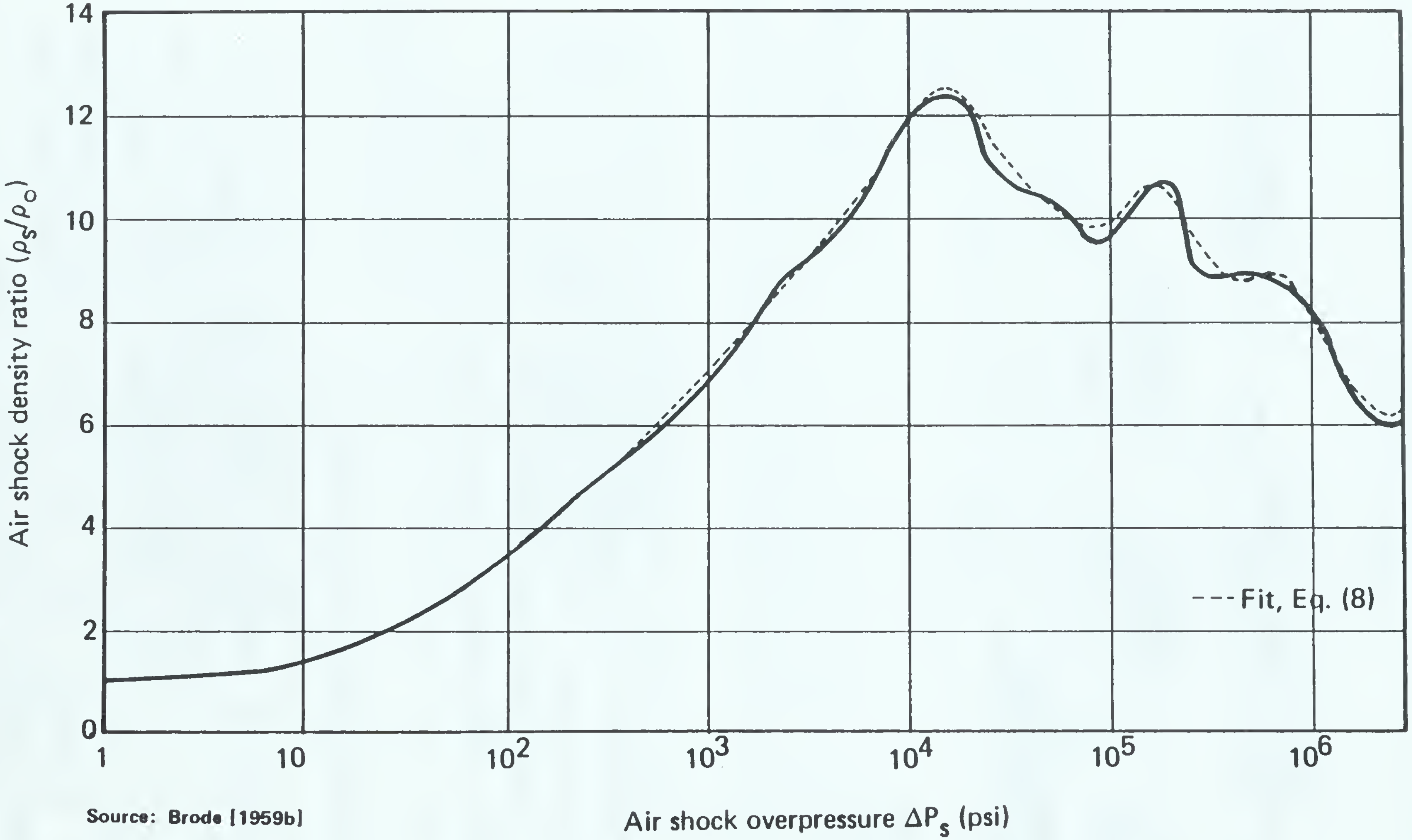
SHOCK DENSITY.

Solving Eqs. (1), (2), and (3) for the shock density as a function of the peak pressure P_s leads to

$$\frac{\rho_s}{\rho_o} = \frac{\left(\frac{\gamma_s + 1}{\gamma_s - 1}\right)\left(\frac{P_s}{P_o}\right) + 1}{\left(\frac{\gamma_o + 1}{\gamma_o - 1}\right) + \frac{P_s}{P_o}} \ . \tag{6}$$

Expressed in terms of shock overpressure ($\Delta P_s \equiv P_s - P_o$), the relation becomes

$$\frac{\rho_s}{\rho_o} = \frac{\left(\frac{\gamma_s + 1}{\gamma_s - 1}\right)\frac{\Delta P_s}{P_o} + \frac{2\gamma_s}{\gamma_s - 1}}{\frac{2\gamma_o}{\gamma_o - 1} + \frac{\Delta P_s}{P_o}} \ . \tag{7}$$



Source: Brode [1959b]

Figure 2. Shock density versus shock overpressure in standard, sea-level air ($\rho_0 \approx 1.293$ kg/m^3).

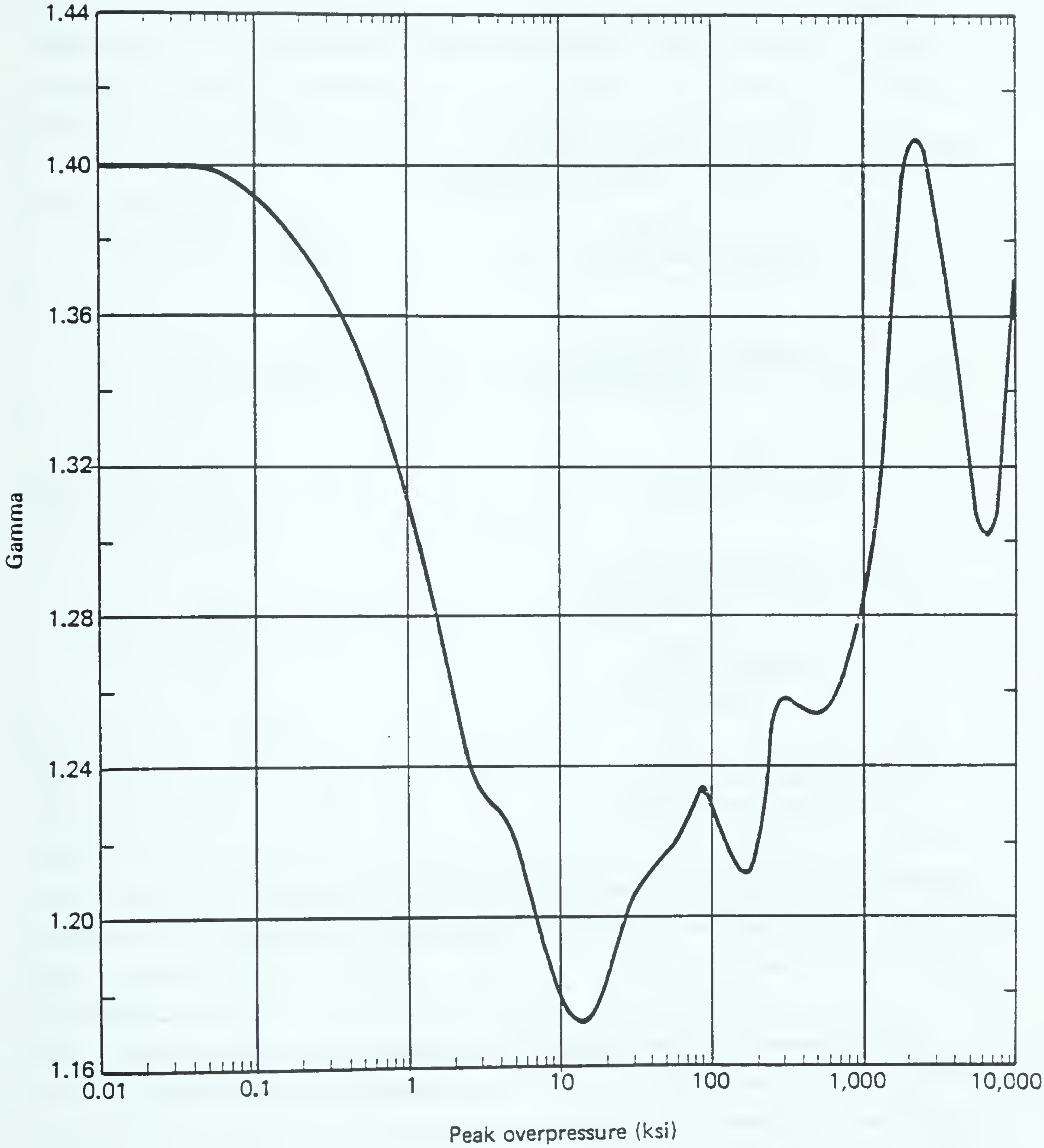


Figure 3. Specific heat ratio ($\gamma \equiv C_p/C_v$) for shocks in standard, sea-level air versus shock pressure.

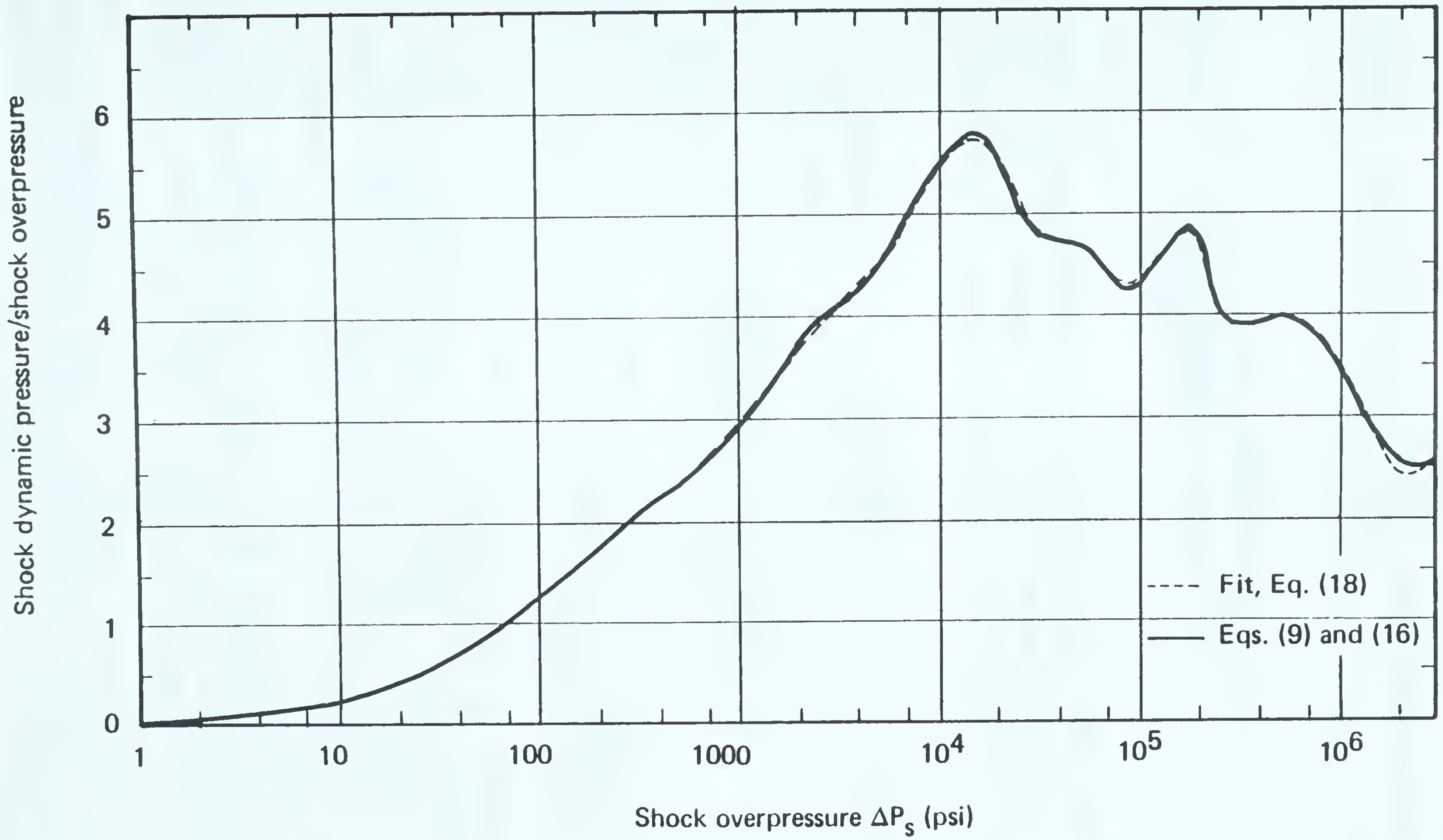


Figure 6. Shock dynamic pressure relative to shock overpressure versus shock overpressure.

NORMAL REFLECTION OF SHOCKS.

When a shock wave strikes a rigid plane head on (as illustrated in Fig. 8), the reflected shock conditions can be derived from conservation considerations similar to those expressed in Eqs. (1), (2), and (4), for mass, momentum, and energy across the reflected shock:

$$\rho_R U_R = (u_s + U_R)\rho_s \qquad \text{(mass)}, \qquad (26)$$

$$P_R - P_s = (u_s + U_R)^2 \rho_s - U_R^2 \rho_R = u_s U_R \rho_R \qquad \text{(momentum)}, \qquad (27)$$

$$\frac{P_R}{\rho_R(\gamma_R - 1)} - \frac{P_s}{\rho_s(\gamma_s - 1)} = \frac{P_R + P_s}{2}\left(\frac{1}{\rho_s} - \frac{1}{\rho_R}\right) \qquad \text{(energy)}, \qquad (28)$$

in which subscripts R refer to conditions after reflection and subscripts s apply to shock values prior to reflection.

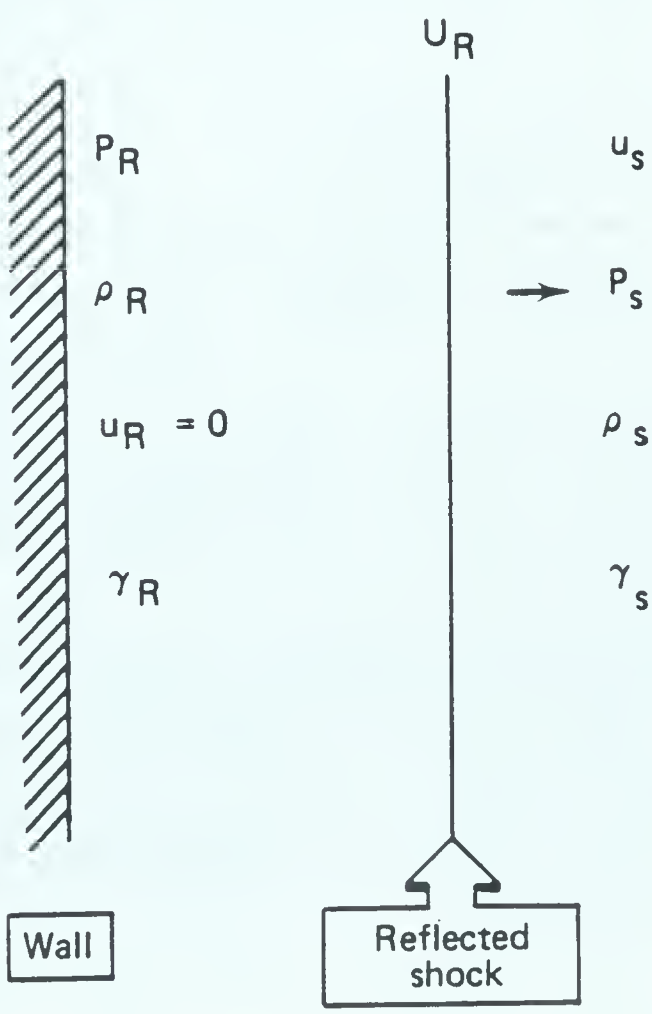


Figure 8. Reflected shock conditions.

Equations (26), (27), and (28) together with the usual Hugoniot relations [Eqs. (1), (2), and (4)], lead to a quadratic in the reflection factor RF ≡ $(\Delta P_R/\Delta P_s)$:

$$\left(\frac{\Delta P_R}{\Delta P_s}\right)^2 + \left(\frac{\Delta P_R}{\Delta P_s}\right)\left\{\left(\frac{\gamma_s - \gamma_R}{\gamma_s - 1}\,\frac{P_o}{\Delta P_s}\right) - \left(\frac{\gamma_s + \gamma_R - 2}{\gamma_s - 1}\right) - (\gamma_R + 1)\right.$$
$$\left.\times \frac{\left[\left(\frac{\gamma_o - 1}{\gamma_s - 1}\right)\Delta P_s - \left(\frac{\gamma_o - \gamma_s}{\gamma_s - 1}\right)P_o\right]}{[2\gamma_o P_o + (\gamma_o - 1)\Delta P_s]}\right\} - \left(\frac{\gamma_s - \gamma_R}{\gamma_s - 1}\right)\frac{P_o}{\Delta P_s} + \left(\frac{\gamma_R - 1}{\gamma_s - 1}\right)$$
$$- \left[\left(\frac{\gamma_o - 1}{\gamma_s - 1}\right) - \frac{P_o}{\Delta P_s}\left(\frac{\gamma_o - \gamma_s}{\gamma_s - 1}\right)\right]\frac{[2\gamma_R P_o + (\gamma_R - 1)\Delta P_s]}{[2\gamma_o P_o + (\gamma_o - 1)\Delta P_s]} = 0 \; . \tag{29}$$

For an ideal gas (where $\gamma_R = \gamma_s = \gamma_o = \gamma$), that expression simplifies to:

$$RF \equiv \frac{\Delta P_R}{\Delta P_s} = \frac{2 + \left(\frac{3\gamma - 1}{2\gamma}\right)\left(\frac{\Delta P_s}{P_o}\right)}{1 + \left(\frac{\gamma - 1}{2\gamma}\right)\left(\frac{\Delta P_s}{P_o}\right)} = 2 + (\gamma + 1)\,\frac{Q_s}{\Delta P_s} \; , \tag{30}$$

in which ΔP_R is the reflected peak overpressure from a normally incident shock of peak overpressure ΔP_s in an ambient atmosphere of pressure P_o, and Q_s is given by Eqs. (16), (17), or (18). Equation (18), though, is an expression for $Q_s/\Delta P_s$ for a shock in real (sea-level) air, and is therefore inconsistent with the ideal gas assumption of Eq. (30).

For air at sea level, a better approximation to the reflection factor RF is given by the formula

$$RF \approx 2 + \frac{2.655\pi}{1 + 0.1728\pi + 0.001921\pi^2} + \frac{0.004218 + 48.34\pi + 6.856\pi^2}{1 + 7.997\pi + 3.844\pi^2} , \qquad (31)$$

where $\pi = \Delta P_s/1000$, (ΔP_s in pounds per square inch).

For a strong shock ($\Delta P_s >> P_o$), the expression in Eq. (29) simplifies to

$$RF \approx 1 + \frac{2\gamma_R}{\gamma_s - 1} . \qquad (32)$$

In Fig. 9, the reflection factor predicted by the approximation in Eq. (31) is compared with a more exact solution from Eq. (29) using the equation of state for air given in Sec. 5 [Eqs. (69) through (74)].

TABLE OF SHOCK VARIABLES.

The shock parameters treated in this section (and plotted in Figs. 2 through 7, and 9) are listed for a range of shock overpressures in Table 1, for standard, sea-level air. The specific heat ratio γ_s is from Eq. (9), the shock density ratio η_s from Eqs. (7) and (9), the shock velocity U_s from Eqs. (9) and (10), the peak particle velocity u_s from Eqs. (9) and (12), and the peak dynamic pressure Q_s from Eqs. (9) and (16). The ratio of the gas constants (thermal) ν is given by Eq. (25); the shock temperature rise $\Delta\theta_s$ is provided by combining Eqs. (9), (20), and (25), and the normal reflection factor RF is arrived at from Eq. (29) and the equation-of-state for air, from Sec. 5, Eqs. (69) through (74).

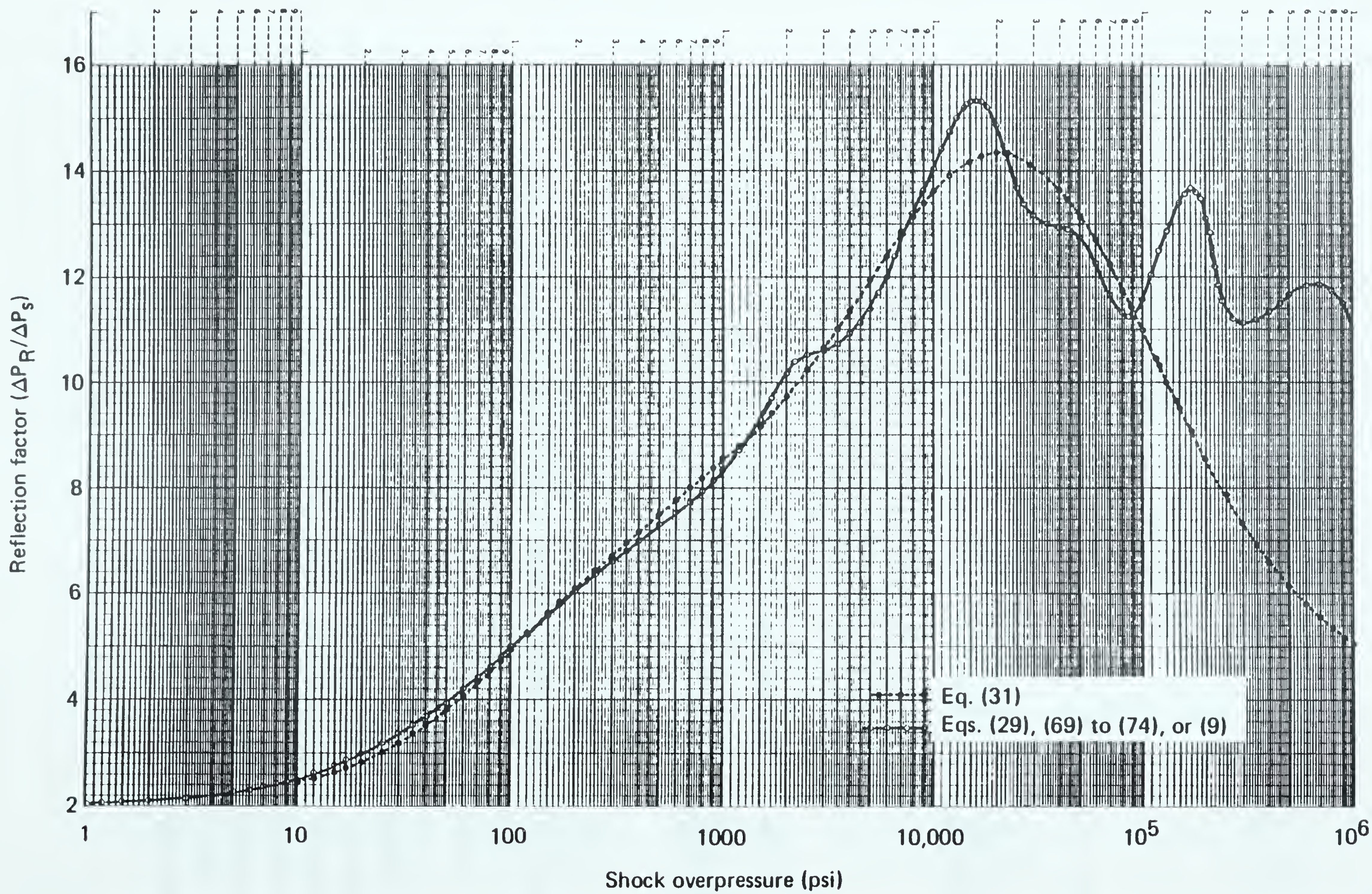


Figure 9. Normal reflection factor versus shock overpressure for sea-level air.

Table 1. Shock variables.

ΔP_S (psi)	$\gamma_S - 1$	η_S (ρ_S/ρ_O)	U_S (kft/s)	u_S (kft/s)	Q_S (psi)	ν_S	$\Delta\theta_S$ (°C)	RF ($\Delta P_R/\Delta P_S$)
.1	.400	1.005	1.090	.00527	.000242	1.00	0.5	2.009
.15	.4	1.007	1.092	.00789	.000545	1.00	0.8	2.012
.2	.4	1.010	1.094	.01051	.00097	1.00	1.1	2.014
.3	.4	1.015	1.097	.01571	.00218	1.00	1.6	2.019
.4	.4	1.019	1.100	.02089	.00387	1.00	2	2.025
.6	.4	1.029	1.106	.0312	.00869	1.00	3	2.035
.8	.4	1.039	1.112	.0413	.01541	1.00	4	2.045
1	.4	1.048	1.118	.0514	.0241	1.00	5	2.055
1.5	.4	1.072	1.134	.0760	.0539	1.00	8	2.080
2	.4	1.095	1.149	.1000	.0953	1.00	10	2.105
3	.4	1.146	1.178	.1462	.2125	1.00	15	2.154
4	.4	1.187	1.207	.1903	.3742	1.00	20	2.202
6	.4	1.275	1.263	.2728	.8264	1.00	28	2.297
7	.4	1.318	1.290	.3116	1.1146	1.00	33	2.343
10	.4	1.443	1.368	.4200	2.214	1.00	45	2.478
15	.4	1.636	1.489	.5788	4.771	1.00	64	2.692
20	.4	1.814	1.600	.7179	8.137	1.00	82	2.891
30	.4	2.129	1.803	.9559	16.93	1.00	117	3.254
40	.4	2.400	1.985	1.158	27.99	1.00	150	3.575
50	.399	2.640	2.150	1.336	41.01	1.00	182	3.862
70	.397	3.043	2.448	1.643	71.50	1.00	244	4.351
100	.392	3.522	2.833	2.028	126.1	1.00	332	4.930
150	.385	4.092	3.378	2.551	231.9	1.00	475	5.629
200	.378	4.508	3.844	2.990	350.8	1.00	612	6.126
300	.368	5.063	4.637	3.718	609.4	1.00	882	6.795
450	.355	5.602	5.612	4.608	1035.5	1.00	1268	7.413
700	.336	6.207	6.927	5.807	1822	1.00	1866	8.043
1000	.312	6.831	8.207	7.002	2916	1.00	2486	8.559
1500	.279	7.728	9.953	8.660	5046	1.00	3359	9.215
2000	.252	8.569	11.409	10.074	7569	1.01	4045	9.758
3000	.237	9.175	13.91	12.39	12263	1.10	5273	10.656
4000	.228	9.565	16.02	14.34	17130	1.18	6313	11.375
6000	.207	10.51	19.52	17.66	28530	1.24	8288	12.430
8000	.191	11.35	22.45	20.47	41390	1.34	9530	13.132
10000	.180	11.99	25.04	22.94	54940	1.46	10340	13.604
15000	.172	12.56	30.60	28.16	86660	1.81	12030	14.20
20000	.179	12.12	35.39	32.46	111200	2.08	14450	14.35
30000	.207	10.65	43.61	39.51	144700	2.62	19750	14.13
40000	.210	10.50	50.39	45.59	190000	3.12	22400	13.66
60000	.218	10.16	61.83	55.74	274800	4.04	26900	12.64
80000	.234	9.537	71.65	64.13	341500	4.76	32500	11.72
100,000	.232	9.612	80.07	71.74	430600	5.19	37000	10.95
150,000	.209	10.56	97.55	88.32	717200	5.90	44500	9.520
200,000	.212	10.43	112.7	101.9	942900	6.74	52600	8.552
300,000	.255	8.841	139.4	123.6	1176000	8.73	72000	7.341
400,000	.2545	8.857	160.9	142.8	1571000	9.75	85800	6.619
600,000	.254	8.873	197.1	174.9	2362000	11.0	113700	5.800
800,000	.264	8.575	228.1	201.5	3030000	11.7	148000	5.346
1000,000	.285	8.017	256.2	224.2	3508000	12.1	192000	5.060
1500,000	.353	6.665	318.4	270.0	4249000	12.3	339000	4.659
2000,000	.400	6.000	371.3	309.4	5000000	12.4	500000	4.449
3000,000	.391	6.115	453.9	379.6	7672000	12.5	731000	4.234
4000,000	.352	6.682	519.8	441.9	11363000	12.7	877000	4.124
6000,000	.304	7.579	630.1	546.5	19740000	13.5	1089000	4.012
8000,000	.316	7.329	729.4	629.9	25320000	15.1	1340000	3.956
10000,000	.363	6.510	828.8	697.2	27550000	16.2	1760000	3.921

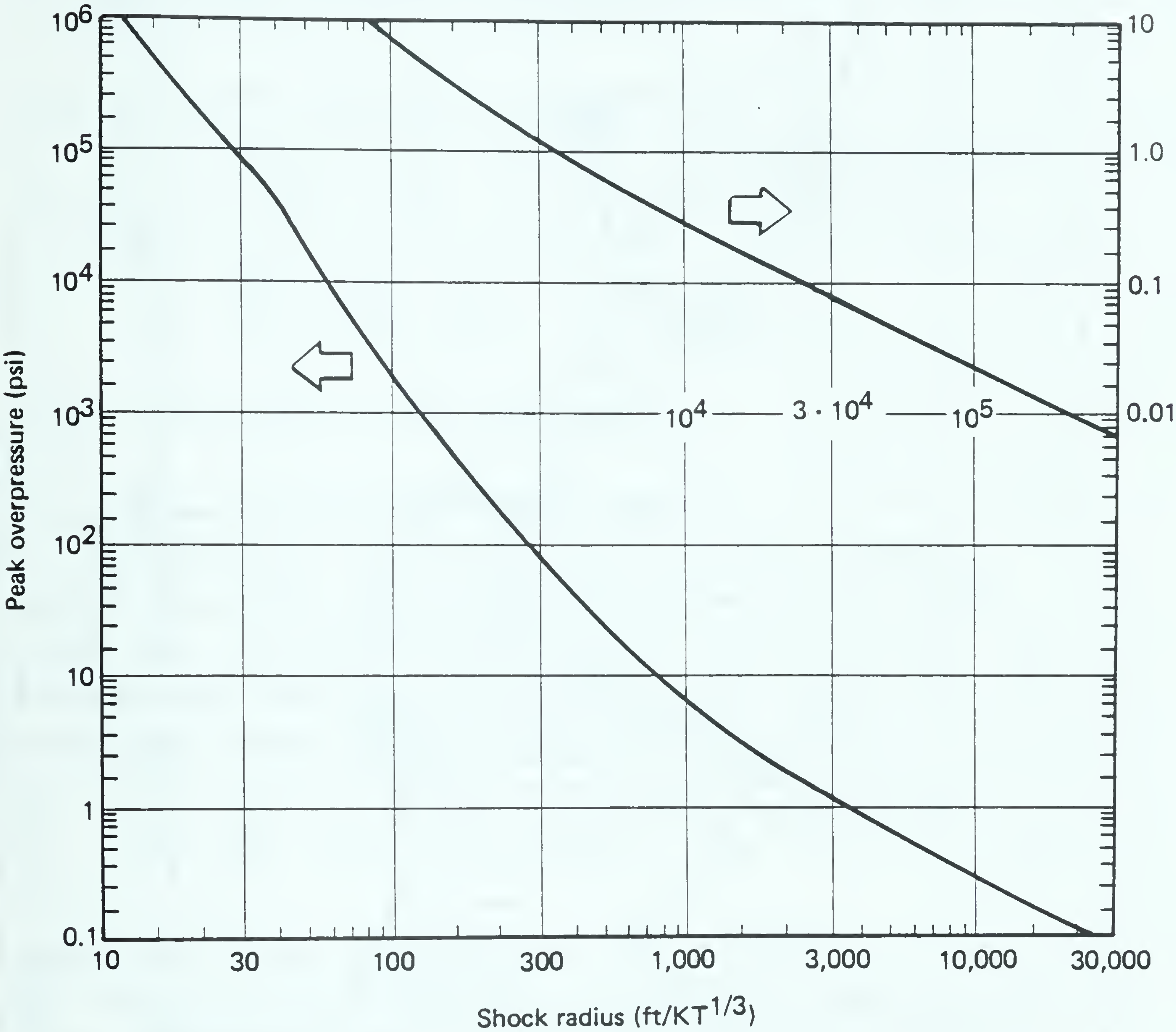


Figure 10. Peak overpressure versus shock radius for 1-KT free-air nuclear burst in standard, sea-level air.

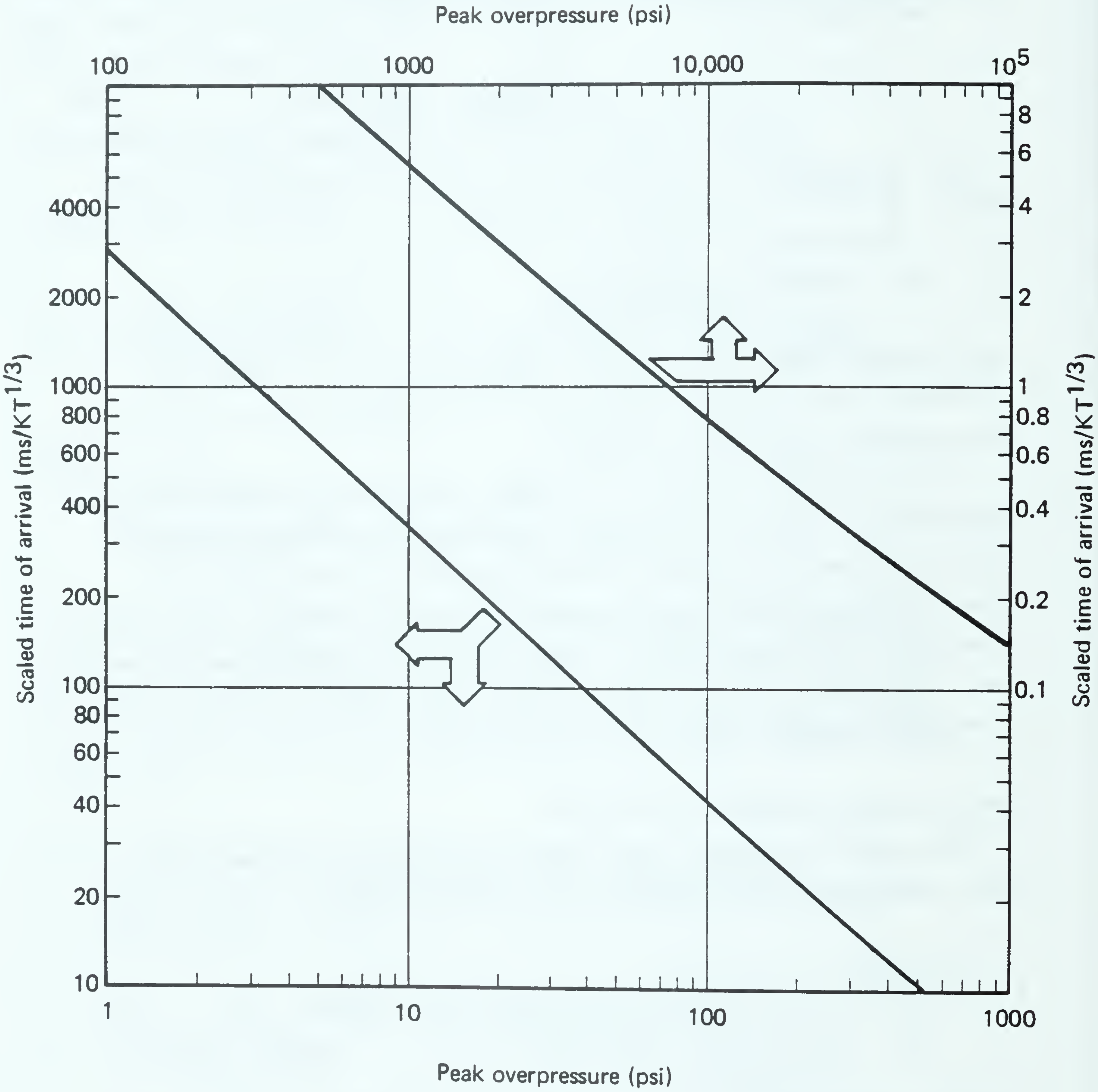


Figure 12. Time of arrival versus peak overpressure for 1-KT free-air burst at sea level.

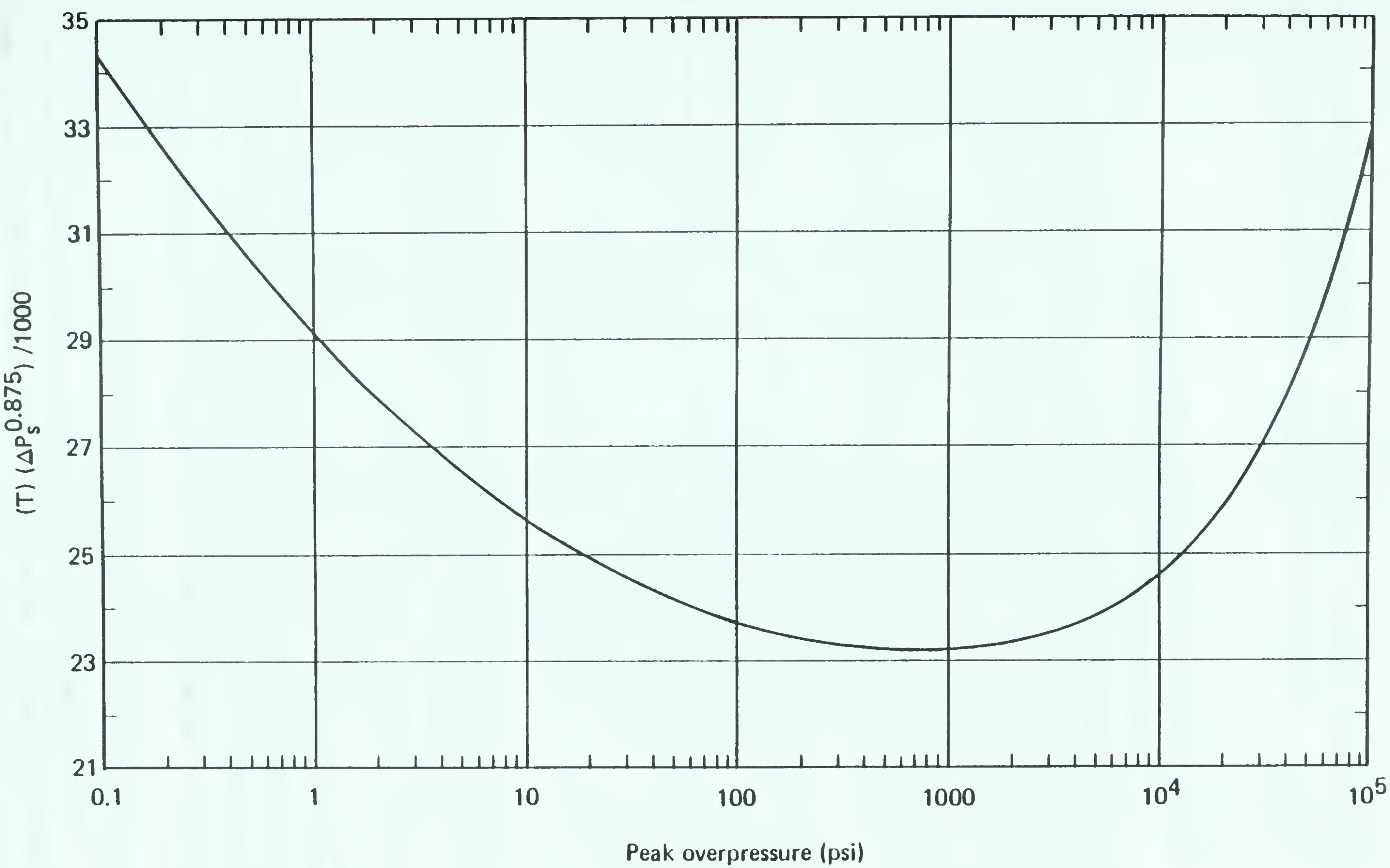


Figure 13. Product of time of arrival and peak overpressure$^{0.875}$ versus peak overpressure for 1 KT (T in milliseconds).

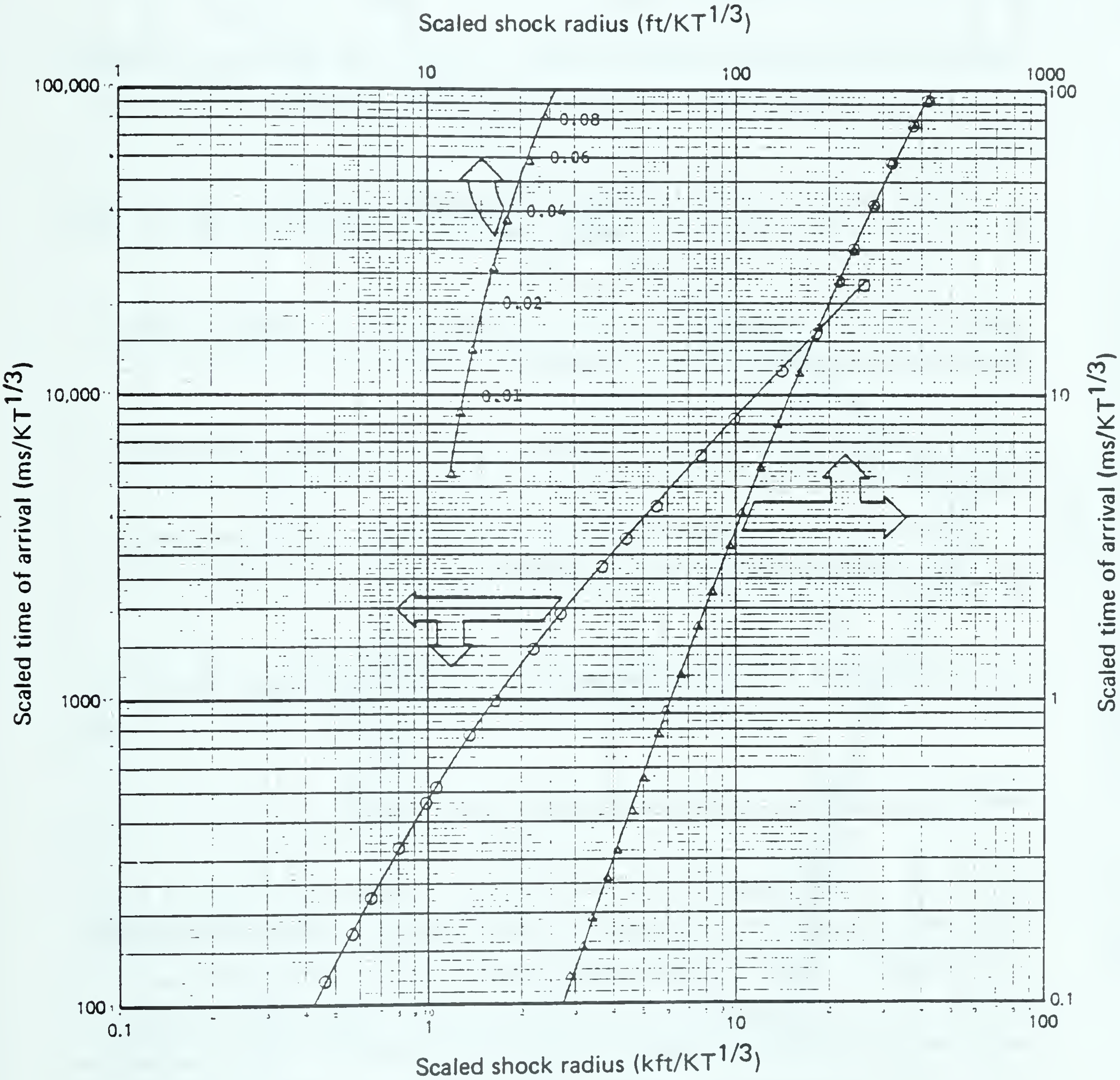


Figure 14. Time of arrival versus shock radius for 1-KT free-air burst.

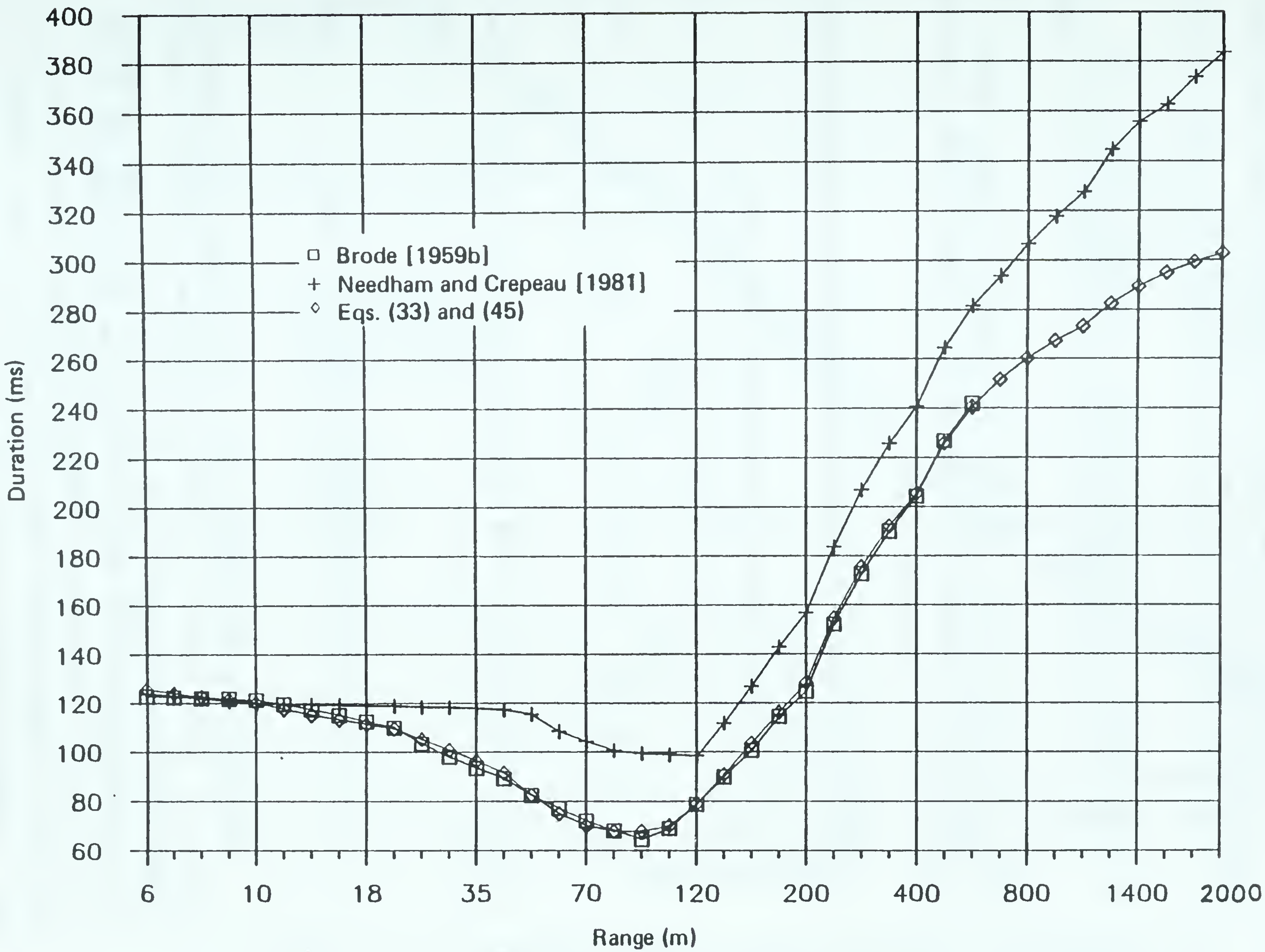


Figure 15. Fit compared to calculations: overpressure durations at 1 KT.

POSITIVE OVERPRESSURE DURATION VERSUS RANGE.

As a function of scaled range (1 KT, free-air burst), the duration of positive overpressure can be approximated by

$$D_p^+ \approx (m)\left[69.12 + \frac{46.19}{(1 + 3{,}000{,}000 r^{7.217})} + \frac{4043 r^{6.329}}{(1 + 37.16 r^{5.621})}\right] \text{ ms,} \tag{46}$$

where r is scaled range in kilofeet per cube-root kiloton. Again, for a surface burst, D_p^+ should be increased by a factor of $2^{1/3}$, i.e., the free-air form for twice the yield.

OVERPRESSURE IMPULSE IN POSITIVE PHASE VERSUS PEAK OVERPRESSURE (FREE-AIR AND SURFACE BURST).

Positive phase impulse I_p^+ is defined by the integral

$$I_p^+ \equiv \int_T^{T+D_p^+} \Delta P(t)\, dt = m \int_\tau^{\tau+D_p^+/m} \Delta P(\sigma)\, d\sigma \ . \tag{47}$$

A simple approximation to this impulse as a function of peak overpressure is

$$I_p^+ \approx \frac{145 \Delta P_s^{1/2}}{(1 + 0.00385 \Delta P_s^{1/2})}\ m \quad \text{psi-ms.} \tag{48}$$

This fit, when used with Eq. (33), leads to the values compared in Fig. 16 versus radius. The impulse approaches a constant at small ranges and decays approximately as the inverse of the range elsewhere. For a surface burst, that expression should be multiplied by 1.26 (i.e., by $2^{1/3}$), which leads to replacing the coefficient 145 by 183. This form is good to better than 10 percent for $2 < \Delta P_s < 100{,}000$ psi. Comparison between the approximation as a function of peak overpressure and the detailed numerical results [Brode, 1964] is made in Fig. 17. In that plot, it is evident that impulse increases

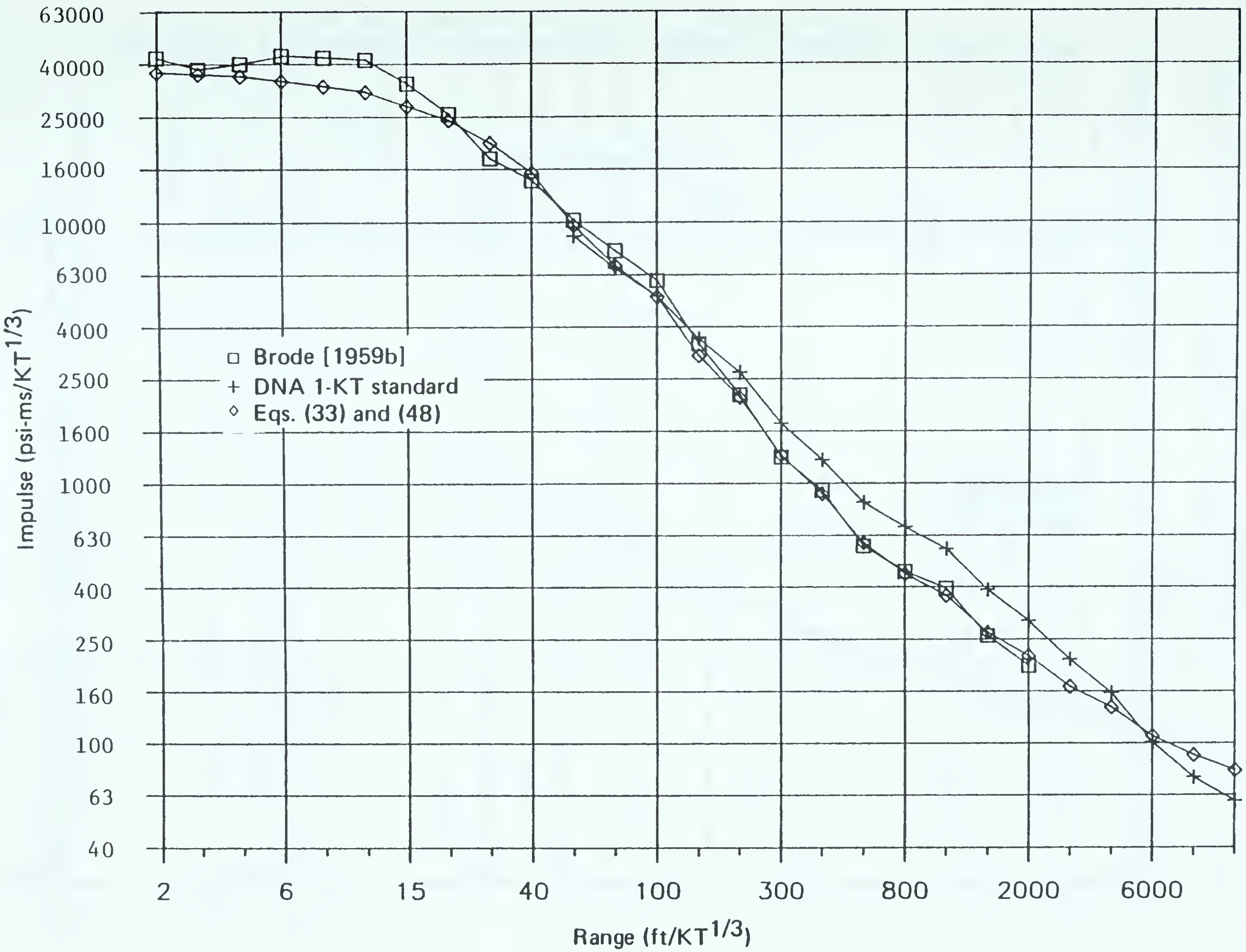


Figure 16. Fit compared to detailed calculation and 1-KT standard: over-pressure impulse in positive phase (1-KT, free-air burst).

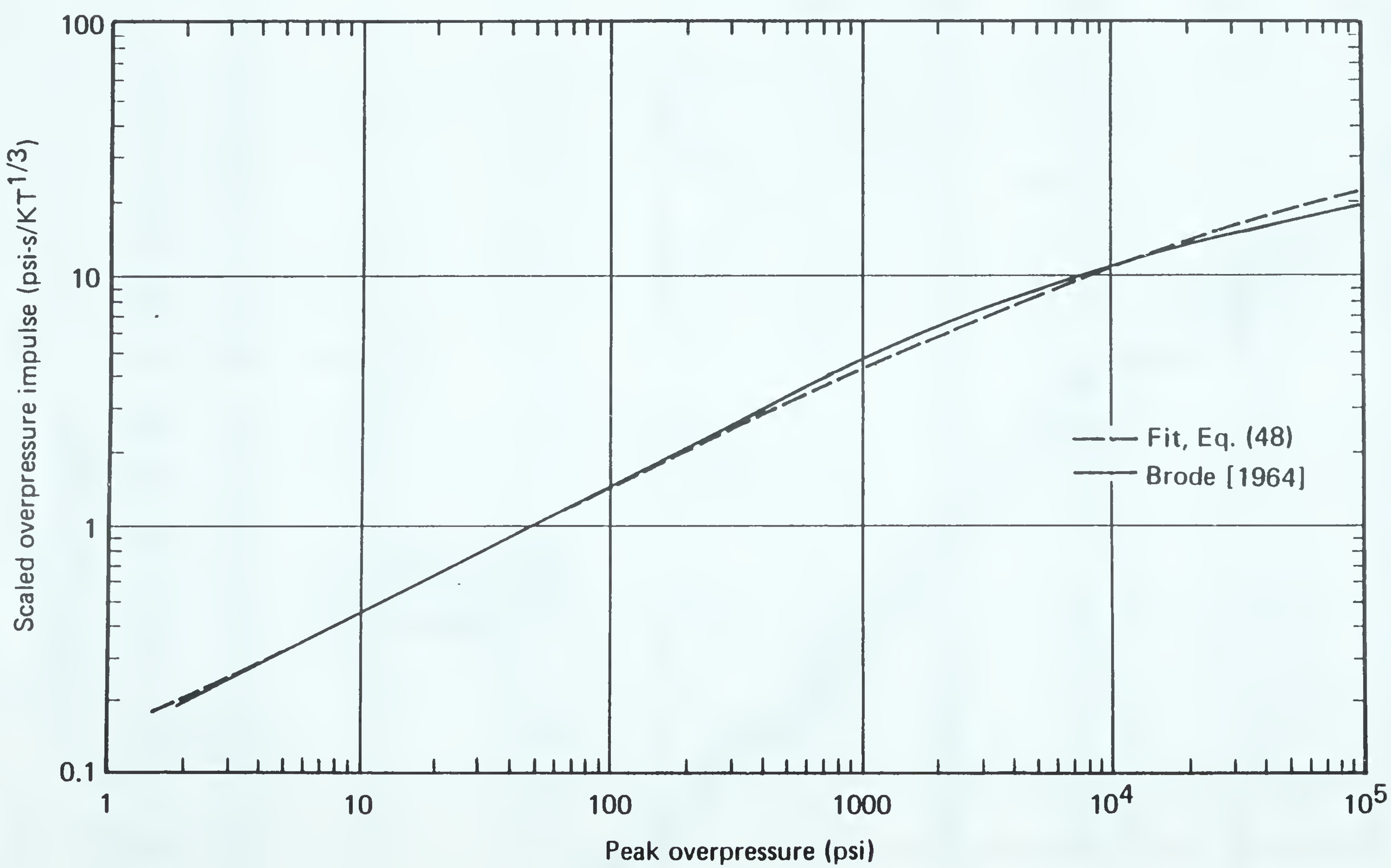


Figure 17. Fit compared to calculation: impulse in positive overpressure versus peak overpressure (1-KT, free-air burst).

approximately as the cube root of overpressure, but tends toward a constant at about a few thousand pounds per square inch.

OVERPRESSURE VERSUS TIME.

The following analytic expression is valid for overpressures less than about 15,000 psi. It is an approximate form, modified from earlier fits [Brode, 1970, 1978] for the overpressure in the positive phase as a function of time. In these fits, time is zero at the instant of burst:

$$\Delta P \approx \Delta P_s(\sigma)\left\{0.417 + 0.583\left(\frac{\tau}{\sigma}\right)^6\left[\frac{40\left(\frac{\tau}{\sigma}\right)^6 + \tau^2}{40 + \tau^2}\right]\right\}\left(1 - \frac{\sigma - \tau}{D_p^+/m}\right) \text{ psi,} \tag{49}$$

where $\Delta P_s(\sigma)$ is found in Eq. (37) and σ replaces τ, $\tau \equiv T/m$, $\sigma \equiv t/m$, T is the time of arrival (in milliseconds), t is the time after time of arrival ($t \geq T$, i.e., $\sigma \geq \tau$). Both T and t are measured from the instant of detonation. The scale factor $m \equiv W^{1/3}$ (in cube-root kilotons) and D_p^+ is the duration of the positive phase [Eqs. (43) through (46)]. As before, for a surface burst, use $m = (2W)^{1/3}$.

OVERPRESSURE VERSUS TIME (SURFACE BURST).

Alternatively, one can use the zero burst height from the more complex equations for height of burst and range [Eq. (63) and Speicher and Brode, 1980a,b, 1981, 1984a,b]. When zero burst height is inserted and expressions are simplified, the calculation for a surface burst becomes

$$\Delta P \approx \Delta P_s(\tau)\left[f\left(\frac{\tau}{\sigma}\right)^g + (1 - f)\left(\frac{\tau}{\sigma}\right)^h\right]\left(1 - \frac{\sigma - \tau}{D}\right) \text{ psi,} \tag{50}$$

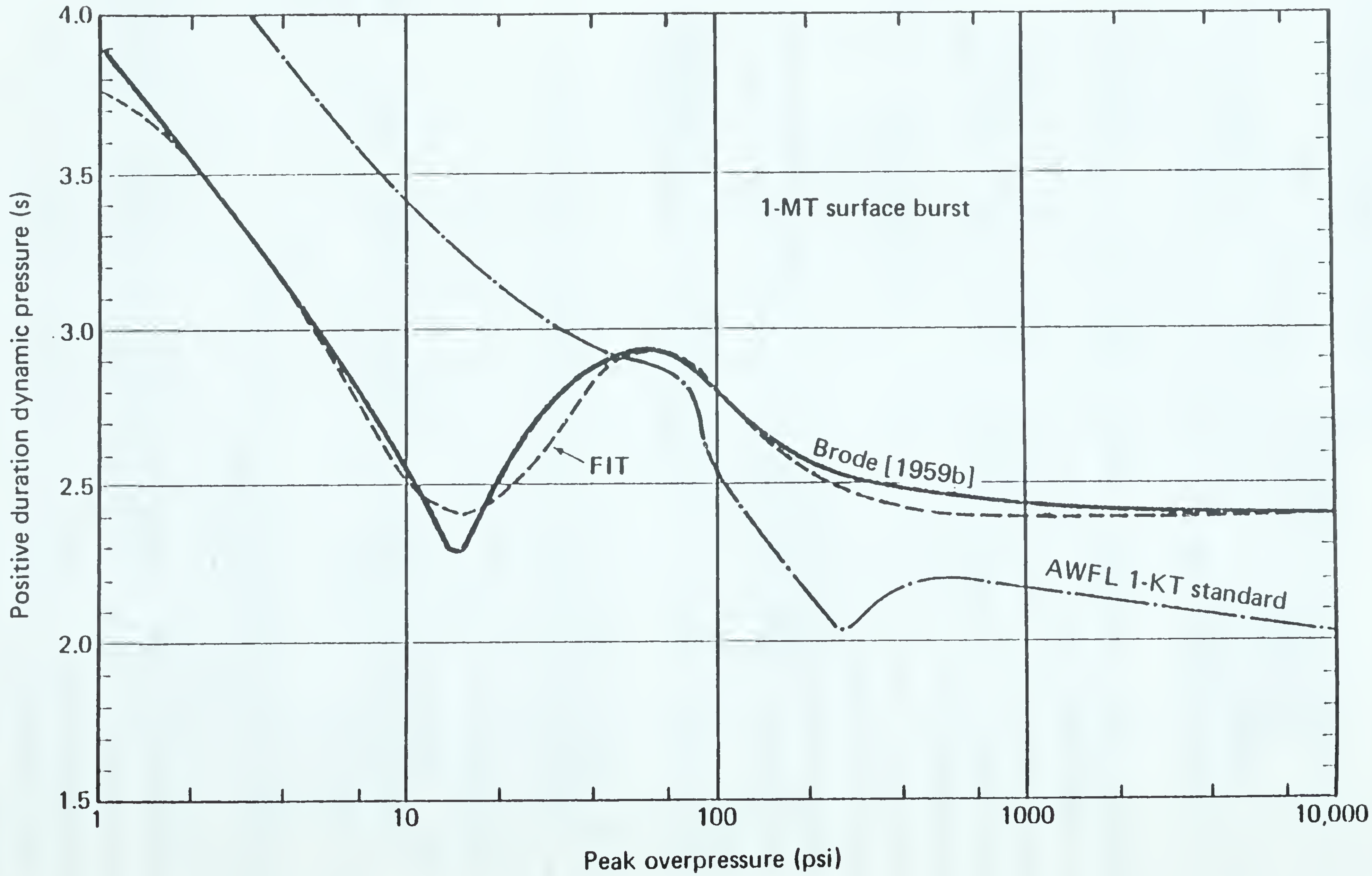


Figure 18. Fit compared to calculation and 1-KT standard (scaled to 1-MT surface burst): dynamic pressure positive phase.

numerical (one-dimensional) calculations is a measure of the differences introduced by dissimilarities in boundary and initial conditions, equations of state and opacities, and by various treatments of radiation transport, thermal radiation losses, and accumulated numerical errors in detailed computer calculations.

DYNAMIC IMPULSE VERSUS PEAK OVERPRESSURE (FREE-AIR BURST).

The dynamic impulse in the positive phase, defined as

$$I_u^+ \equiv (1/2) \int_T^{T+D_u^+} \rho u^2 \, dt \, , \tag{53}$$

can be approximated as

$$I_u^+ \approx \frac{2.14 \Delta P_s^{1.637} (m)}{(1 + 0.00434 \Delta P_s^{1.431})} \quad \text{psi-ms.} \tag{54}$$

That form is within 10 percent of the scaled values from the detailed calculations [Brode, 1959b, 1966] for $3 < \Delta P_s < 10{,}000$ psi. It is high by nearly 20 percent at $\Delta P_s \approx 100{,}000$ psi. Figure 19 compares the dynamic impulse from the detailed calculations with that from this fit (Eq. 54).

DYNAMIC IMPULSE VERSUS SCALED RANGE.

A fit to the dynamic impulse versus range for the early calculations [Brode, 1959b] agrees to better than 10 percent for $0.0025 \leqq r \leqq 2$ kft/KT$^{1/3}$. The relation, when scaled to a 1-KT free-air burst, is

$$I_u^+ = \left[\frac{18.8 r^2}{10^{-6} + 0.06896 r^3 + 0.5963 r^{5.652}} + \frac{92.64}{(100r)^5} + \frac{2935(r - 0.00597)(0.01 - r)(0.0003552 - r^4)}{10^{-10} + 0.003377 r^{2.5} + 155.8 r^8} \right] m \quad \text{psi-ms,} \tag{55}$$

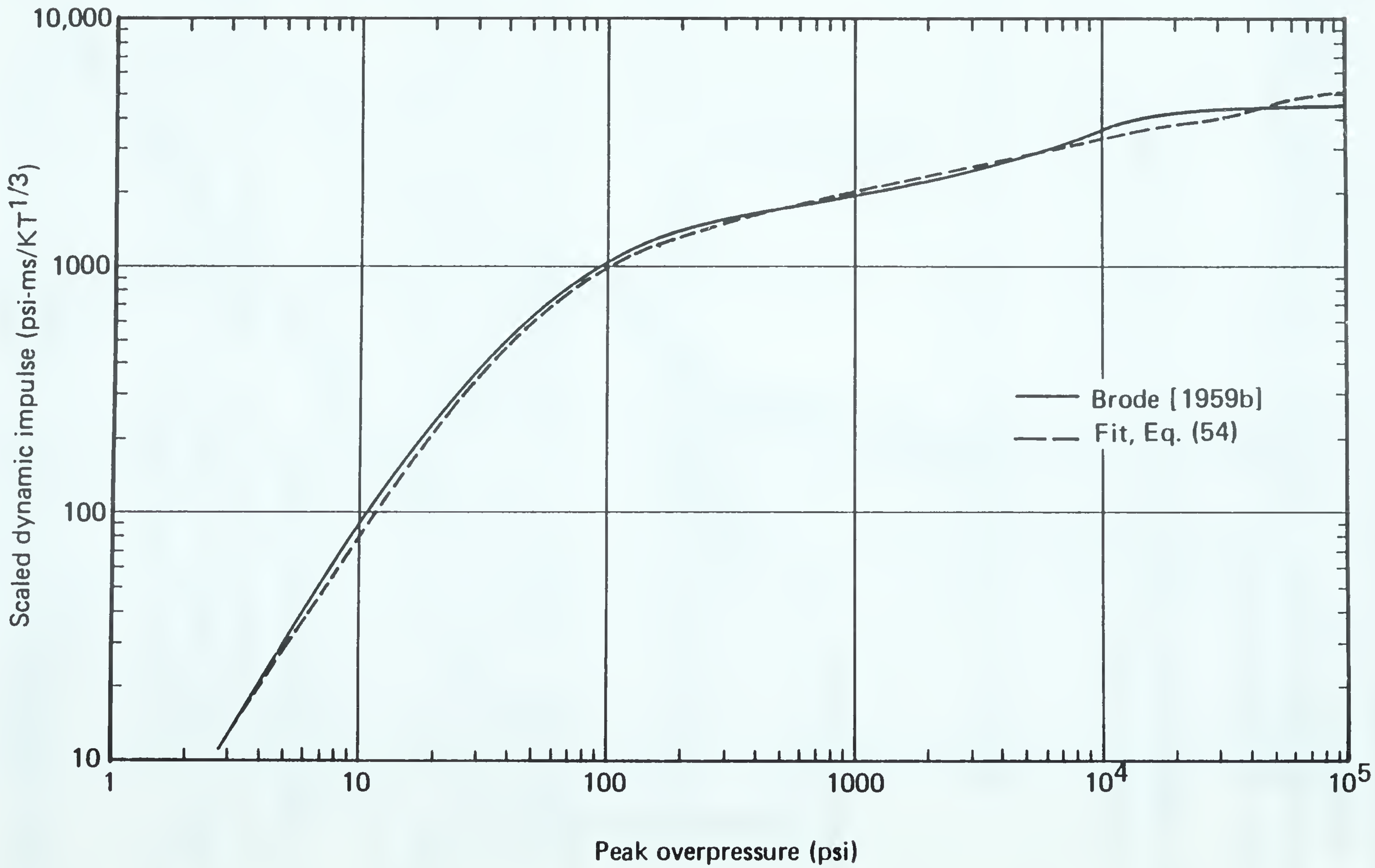


Figure 19. Fit compared to calculation: dynamic impulse versus peak overpressure for 1-KT free-air burst.

with $r = sr/m$, sr in kilofeet, $m = W^{1/3}$, and W in kilotons. This expression is illustrated in Fig. 20 and compared with the detailed calculation results to which it was fit. The fit is good to a few percent over the entire range. For a surface burst, $m = (2W)^{1/3}$.

DYNAMIC PRESSURE VERSUS TIME.

An older approximate analytic expression for dynamic pressure versus time covers the range $2 \leq \Delta P_X \leq 1000$ psi ($0.1 \leq Q_S \leq 3000$ psi) [Brode, 1964]:

$$Q(t) = Q_s(1 - \omega)^2 \left[d \exp(-a\omega) + (1 - d) \exp(-b\omega)\right] \quad \text{psi}, \qquad (56)$$

in which $\omega \equiv (t - T)/D_u^+$,

$T \equiv$ time of arrival [see Eqs. (39) through (41)],

$t \equiv$ time,

$D_u^+ \equiv$ duration of outward blast wind [see Eq. (52)],

$Q_S \equiv$ peak dynamic pressure in pounds per square inch [see Eqs. (16) through (18)],

$$d \approx \frac{1.06\pi^{0.035}}{1 + 147\pi^3} + \frac{2.13\pi^3}{1 + 67.9\pi^{3.5}} ,$$

$$a \approx 0.38\Delta P_s^{0.8605} \approx 145\pi^{0.8605} ,$$

$$b \approx 5.4\Delta P_s^{0.604} \approx 350\pi^{0.604} .$$

Equation (56) is valid for $1 \geq \pi \geq 0.002$ ksi ($1000 \geq \Delta P_X \geq 2$ psi). These parameters are illustrated in Fig. 21 (scaled to 1-MT surface burst).

A relatively simple alternative surface burst formula for dynamic pressure versus time can be derived from the more complex fits to dynamic and overpressure versus HOB, ground range, and time [Speicher, 1983; Speicher and Brode, 1981; Brode, 1983]. That fit, when simplified for zero HOB, becomes essentially that of the shock or

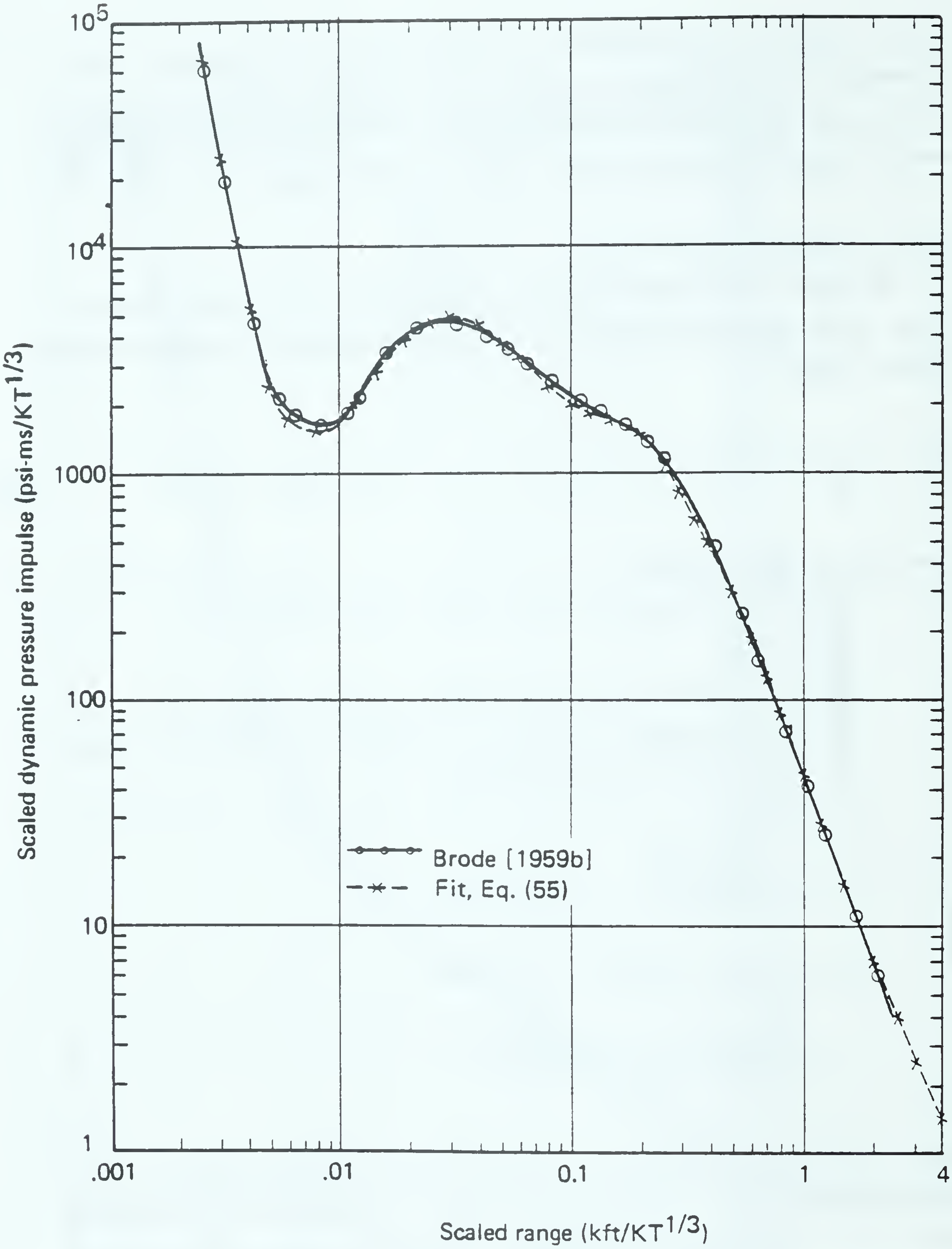
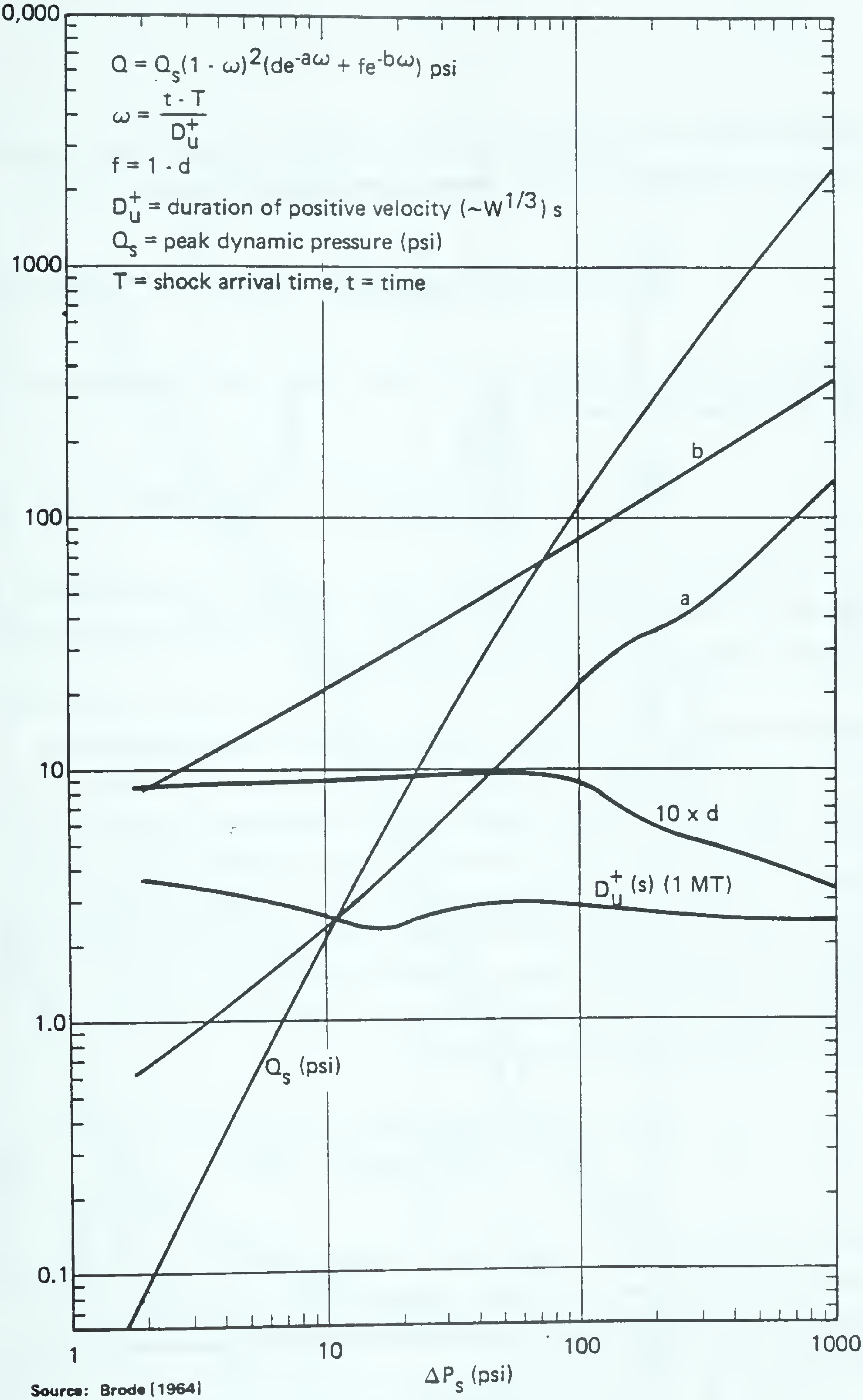


Figure 20. Fit compared to calculation: scaled dynamic pressure impulse versus scaled range for 1-KT free-air burst.



Source: Brode (1964)

Figure 21. Dynamic pressure versus peak overpressure and time (scaled for 1-MT surface burst).

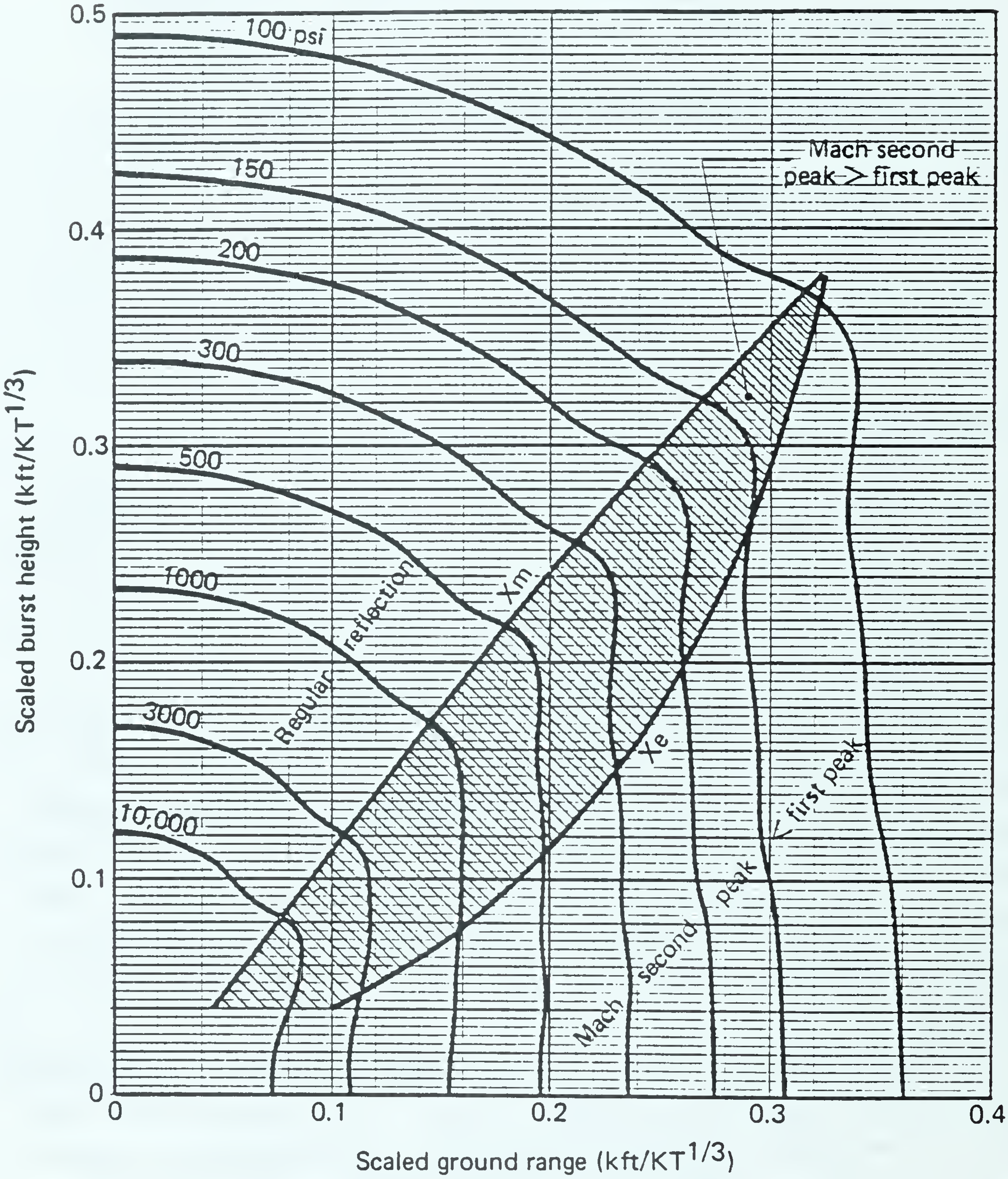


Figure 41. High peak overpressures versus scaled burst height and scaled ground range (ideal surface).

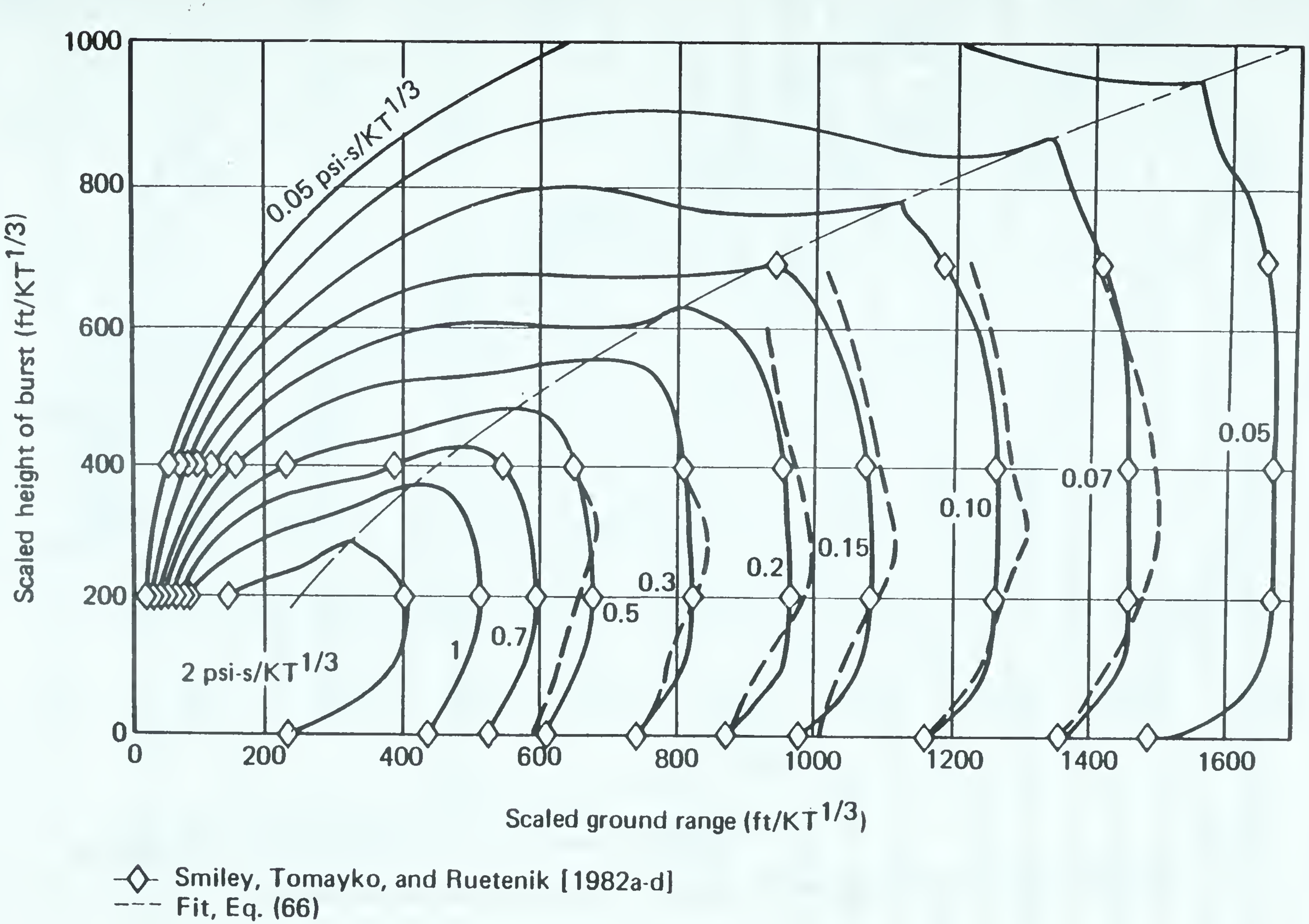


Figure 110. Integration of Eq. (66) over positive phase compared to Kaman AviDyne calculations: dynamic impulse versus SHOB and scaled ground range.

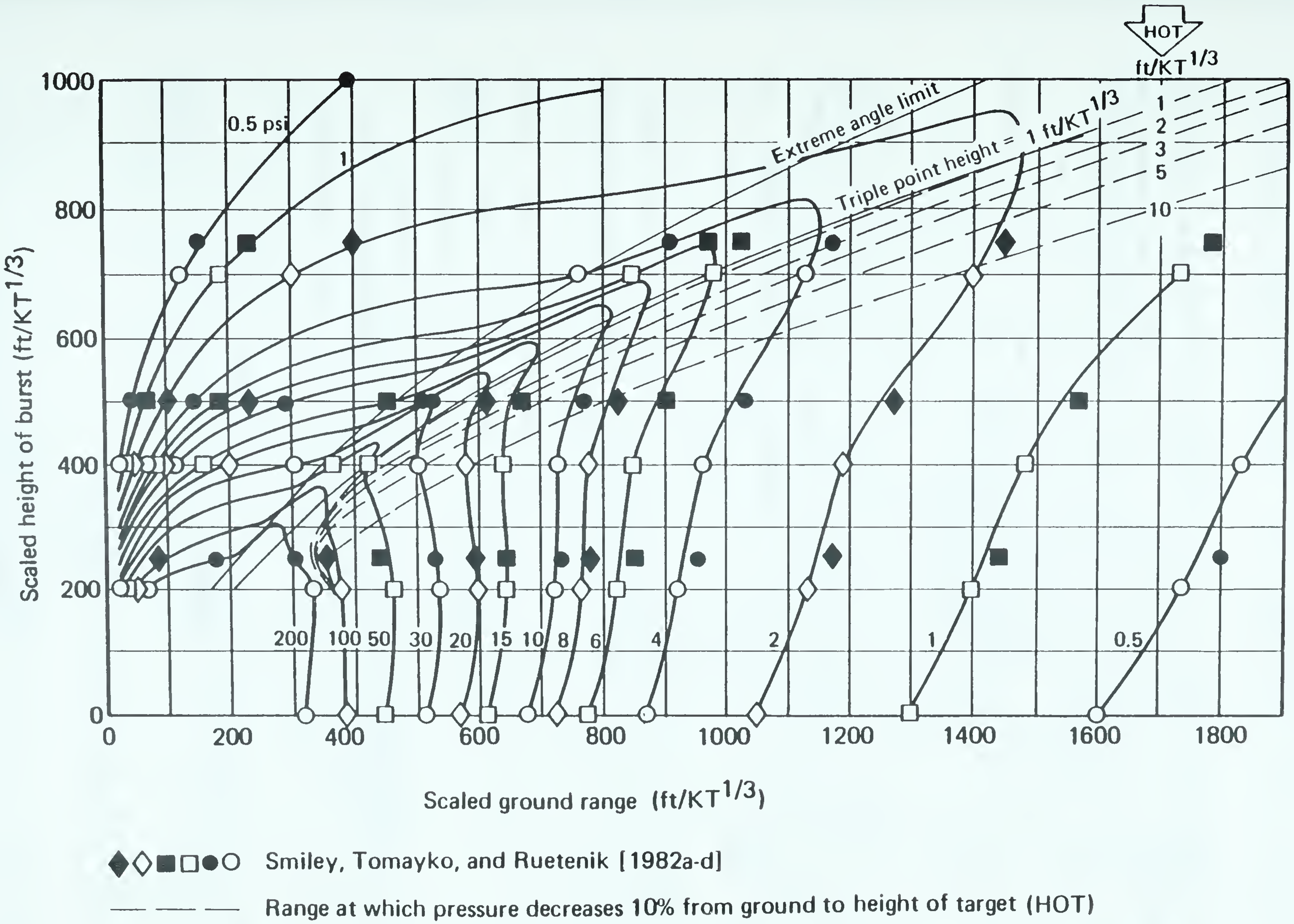


Figure 111. Maximum dynamic pressure HOB/HOT contours for scaled target heights of scaled burst height and ground range where peak dynamic pressure is 90 percent of surface value.

SECTION 5
EQUATION OF STATE FOR AIR

For strong blast waves in the atmosphere, the real gas (nonideal gas) properties of air become important, and the ideal gas assumptions frequently prove inadequate. Air molecules enter a complex energy-density-pressure balance as they dissociate and ionize with rising pressure or temperature. Their behavior is expressed in thermodynamic terms from detailed calculations [Gilmore, 1955, 1959; Hilsenrath, Green, and Beckett, 1957]. The equation of state for air has been closely fit by the author [Brode and Parkin, 1963] and that fit has been used in detailed numerical calculations of the radiation flow and hydrodynamics of nuclear bursts [Brode, 1959a,b, 1966, 1969; Brode et al., 1967], as well as in the KA calculations [Smiley, Tomayko, and Ruetenik, 1982a-d].

CALORIC EQUATION OF STATE FOR AIR.

The usual ideal gas relation for specific internal energy can be written as

$$E = \frac{P}{\rho(\gamma - 1)} , \qquad (69)$$

in which E is the energy per unit mass, P is the pressure, ρ is the density, and γ is the ratio of specific heats ($\gamma \equiv C_p/C_v$). Defining $\mu \equiv (\gamma + 1)/(\gamma - 1)$, one can rewrite Eq. (69) as

$$P = \frac{2\rho E}{(\mu - 1)} . \qquad (70)$$

Using a dimensionless variable defined as

$$\phi \equiv \left(\frac{P_o}{P}\right)\left(\frac{\rho}{\rho_o}\right)^{1.0553} , \qquad (71)$$

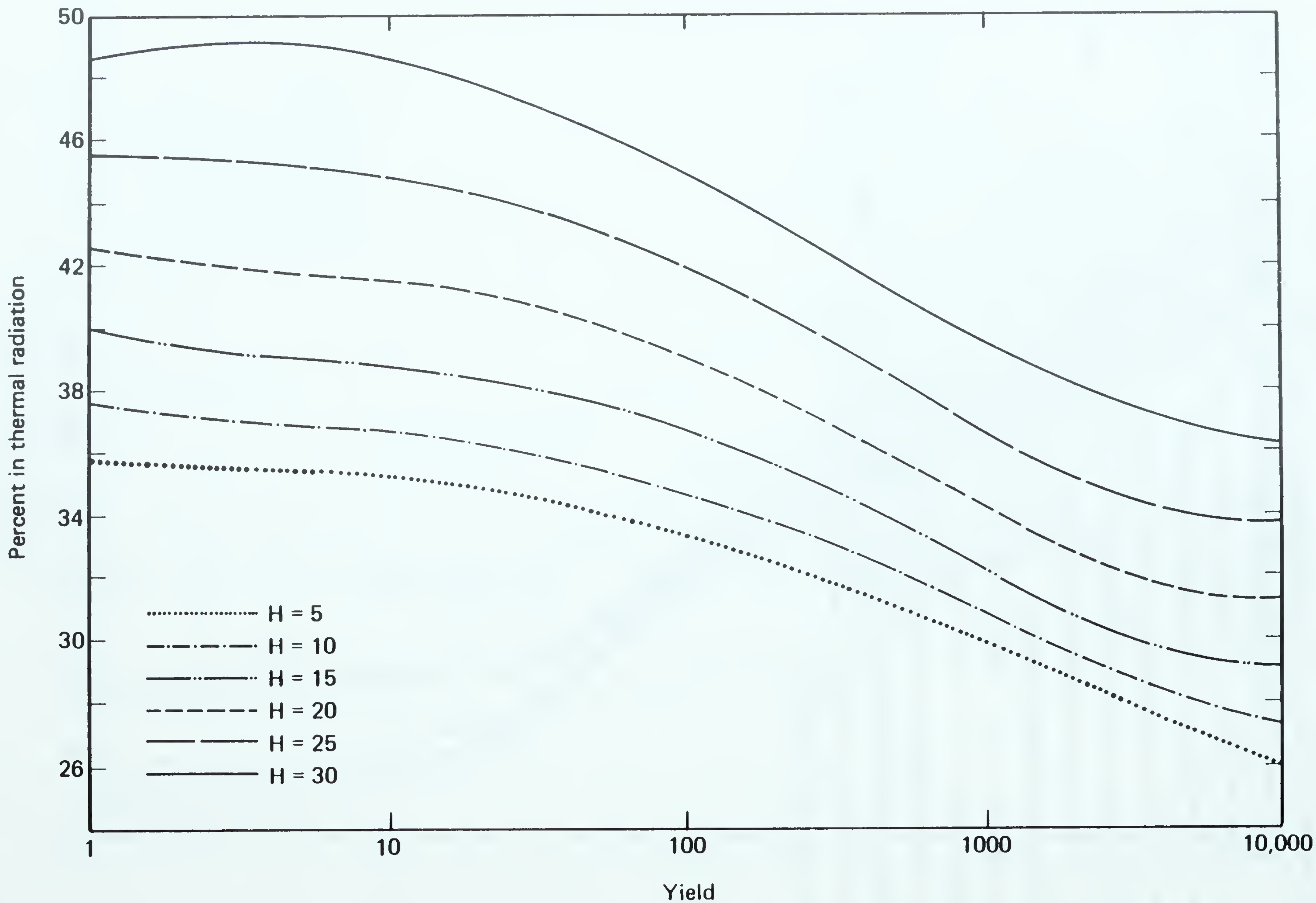


Figure 119. Thermal radiation fraction of total yield versus yield for burst altitudes up to 30 KM [EM-1, 1985].

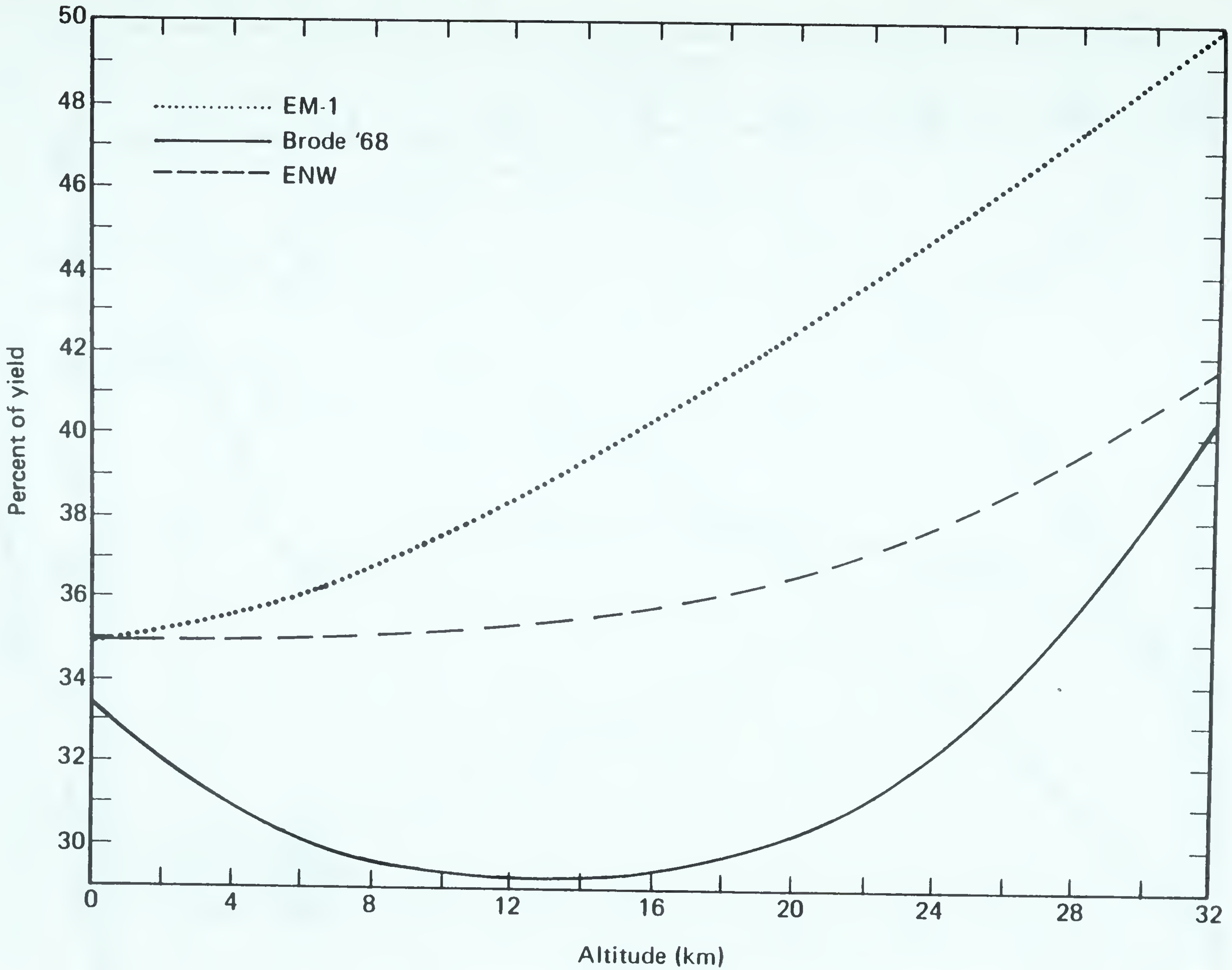


Figure 120. Comparison of thermal fractions as predicted by three formulae (Eqs. (101), (102), (103)) versus burst altitude for 1 KT.

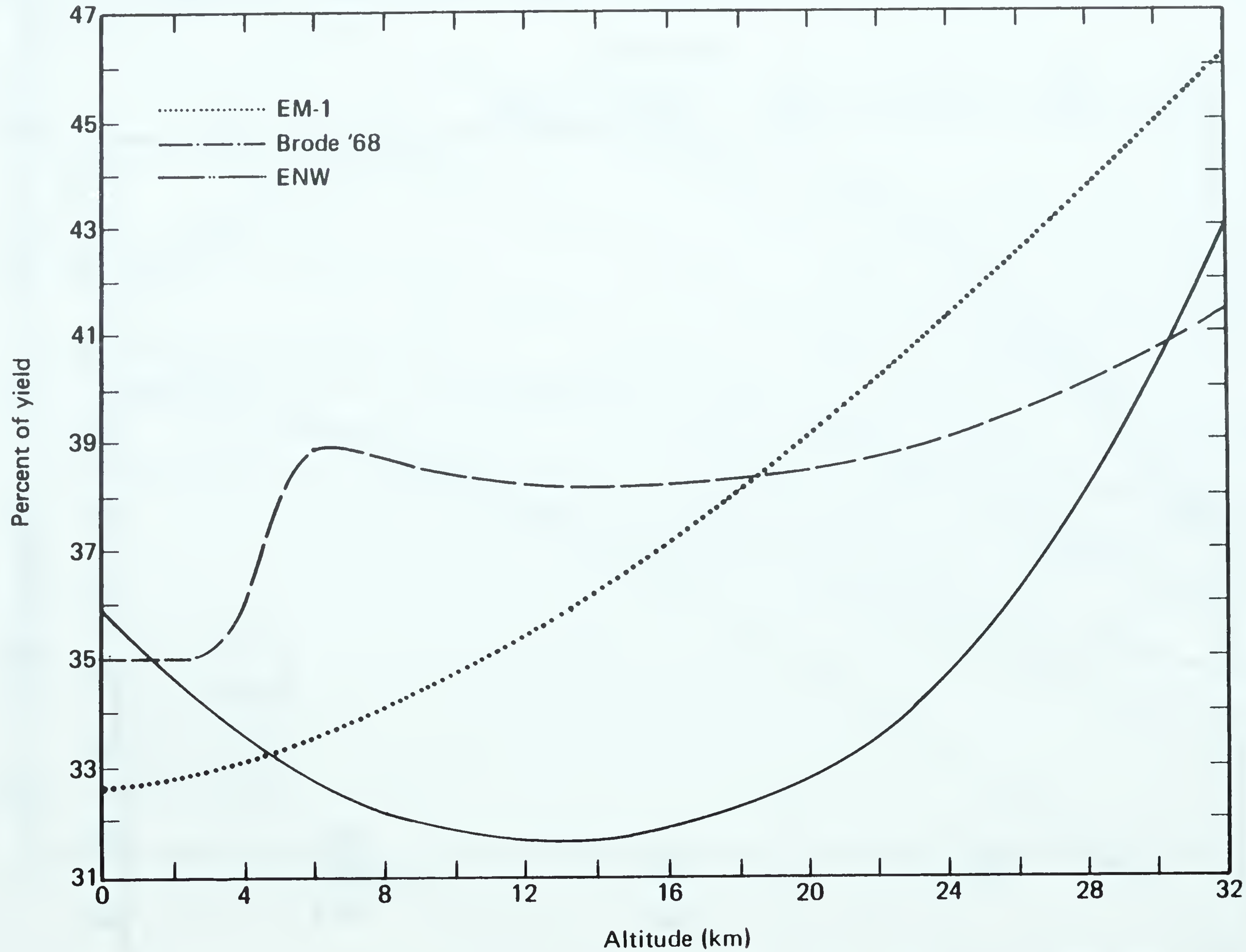


Figure 121. Comparison of thermal fractions as predicted by three formulae (Eqs. (101), (102), (103)) versus burst altitude for 100 KT.

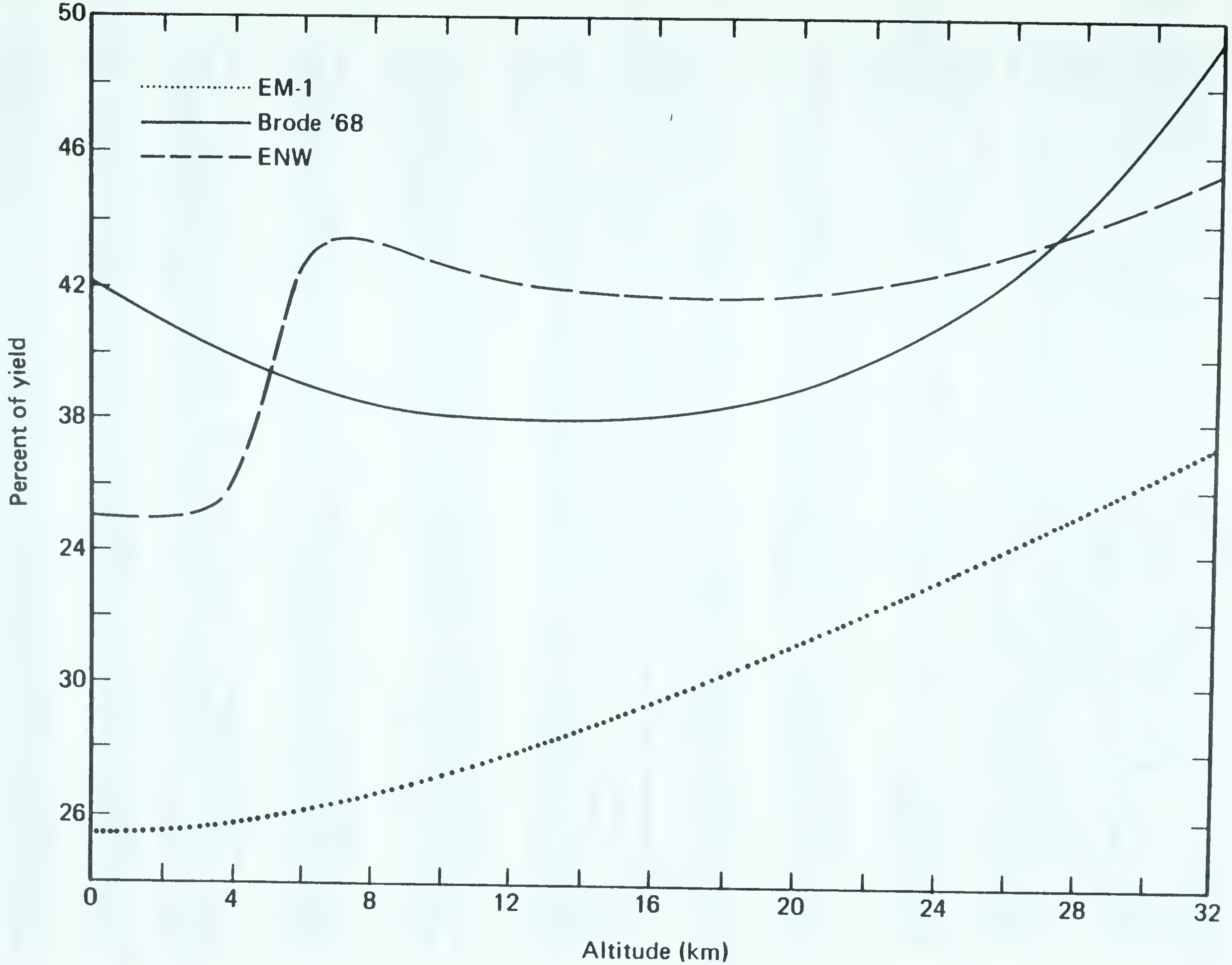


Figure 122. Comparison of thermal fractions as predicted by three formulae (Eqs. (101), (102), (103)) versus burst altitude for 10 MT.

SECTION 7

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